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SECTION 3

MEASUREMENTS AND INSTRUMENTS*

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CONTENTS

3.1	ELECTRIC AND MAGNETIC MEASUREMENTS	3-1
3.1.1	General	3-1
3.1.2	Detectors and Galvanometers	3-4
3.1.3	Continuous EMF Measurements	3-9
3.1.4	Continuous Current Measurements	3-13
3.1.5	Analog Instruments	3-14
3.1.6	DC to AC Transfer	3-16
3.1.7	Digital Instruments	3-16
3.1.8	Instrument Transformers	3-18
3.1.9	Power Measurement	3-19
3.1.10	Power-Factor Measurement	3-21
3.1.11	Energy Measurements	3-22
3.1.12	Electrical Recording Instruments	3-27
3.1.13	Resistance Measurements	3-29
3.1.14	Inductance Measurements	3-38
3.1.15	Capacitance Measurements	3-41
3.1.16	Inductive Dividers	3-45
3.1.17	Waveform Measurements	3-46
3.1.18	Frequency Measurements	3-46
3.1.19	Slip Measurements	3-48
3.1.20	Magnetic Measurements	3-48
3.2	MECHANICAL POWER MEASUREMENTS	3-51
3.2.1	Torque Measurements	3-51
3.2.2	Speed Measurements	3-51
3.3	TEMPERATURE MEASUREMENT	3-52
3.4	ELECTRICAL MEASUREMENT OF NONELECTRICAL QUANTITIES	3-56
3.5	TELEMETERING	3-61
3.6	MEASUREMENT ERRORS	3-64
	BIBLIOGRAPHY	3-66

3.1 ELECTRIC AND MAGNETIC MEASUREMENTS

3.1.1 General

Measurement of a quantity consists either of its comparison with a unit quantity of the same kind or of its determination as a function of quantities of different kinds whose units are related to it by known physical laws. An example of the first kind of measurement is the evaluation of a resistance

*Grateful acknowledgement is given to Norman Belecki, George Burns, Forest Harris, and B.W. Mangum for most of the material in this section.

(in ohms) with a Wheatstone bridge in terms of a calibrated resistance and a ratio. An example of the second kind is the calibration of the scale of a wattmeter (in watts) as the product of current (in amperes) in its field coils and the potential difference (in volts) impressed on its potential circuit.

The units used in electrical measurements are related to the metric system of mechanical units in such a way that the electrical units of power and energy are identical with the corresponding mechanical units. In 1960, the name *Système International* (abbreviated SI), now in use throughout the world, was assigned to the system based on the meter-kilogram-second-ampere (abbreviated mksa). The mksa units are identical in value with the practical units—volt, ampere, ohm, coulomb, farad, henry—used by engineers. Certain prefixes have been adopted internationally to indicate decimal multiples and fractions of the basic units.

A *reference standard* is a concrete representation of a unit or of some fraction or multiple of it having an assigned value which serves as a measurement base. Its assignment should be traceable through a chain of measurements to the National Reference Standard maintained by the National Institute of Standards and Technology (NIST). Standard cells and certain fixed resistors, capacitors, and inductors of high quality are used as reference standards.

The National Reference Standards maintained by the NIST comprise the legal base for measurements in the United States. Other nations have similar laboratories to maintain the standards which serve as their measurement base. An international bureau—Bureau International des Poids et Mesures (abbreviated BIPM) in Sèvres, France—also maintains reference standards and compares standards from the various national laboratories to detect and reconcile any differences that might develop between the as-maintained units of different countries.

At NIST, the reference standard of resistance is a group of 1- Ω resistors, fully annealed and mounted strain-free out of contact with the air, in sealed containers. The reference standard of capacitance is a group of 10-pF fused-silica-dielectric capacitors whose values are assigned in terms of the calculable capacitor used in the ohm determination. The reference standard of voltage is a group of standard cells continuously maintained at a constant temperature.

The “absolute” experiments from which the value of an electrical unit is derived are measurements in which the electrical unit is related directly to appropriate mechanical units. In recent *ohm* determinations, the value of a capacitor of special design was calculated from its measured dimensions, and its impedance at a known frequency was compared with the resistance of a special resistor. Thus, the ohm was assigned in terms of length and time. The as-maintained ohm is believed to be within 1 ppm of the defined SI unit. Recent *ampere* determinations, used to assign the *volt* in terms of current and resistance, derived the ampere by measuring the force between current-carrying coils of a mutual inductor of special construction whose value was calculated from its measured dimensions. The voltage drop of this current in a known resistor was used to assign the emf of the standard cells which maintain the volt. The stated uncertainty of these ampere determinations ranges from 4 to 7 ppm, and the departure of value of the “legal” volt from the defined SI unit carries the same uncertainty. Since 1972, the assigned emf of the standard cells in the reference group which maintains the legal volt is monitored (and reassigned as necessary) in terms of atomic constants (the ratio of Planck’s constant to electron charge) and a microwave frequency by an ac Josephson experiment in which their voltage is measured with respect to the voltage developed across the barrier junction between two superconductors irradiated by microwave energy and biased with a direct current. This experiment appears to be repeatable within 0.1 ppm. It should be noted that while the Josephson experiment may be used to maintain the legal volt at a constant level, it is not used to define the SI unit.

Precision—a measure of the spread of repeated determinations of a particular quantity—depends on various factors. Among these are the resolution of the method used, variations in ambient conditions (such as temperature and humidity) that may influence the value of the quantity or of the reference standard, instability of some element of the measuring system, and many others. In the National Laboratory of the National Institute of Standards and Technology, where every precaution is taken to obtain the best possible value, intercomparisons may have a precision of a few parts in 10^7 . In commercial laboratories, where the objective is to obtain results that are reliable but only to the extent justified by engineering or other requirements, precision ranges from this figure to a part in 10^3 or more, depending on circumstances. For commercial measurements such as the sale of electrical energy, where the cost of measurement is a critical factor, a precision of 1 or 2% is considered acceptable in some jurisdictions.

The use of digital instruments occasionally creates a problem in the evaluation of precision, that is, all results of a repeated measurement may be identical due to the combination of limited resolution and quantized nature of the data. In these cases, the least count and sensitivity of the instrumentation must be taken into account in determining precision.

Accuracy—a statement of the limits which bound the departure of a measured value from the true value of a quantity—includes the imprecision of the measurement, together with all the accumulated errors in the measurement chain extending downward from the basic reference standards to the specific measurement in question. In engineering measurement practice, accuracies are generally stated in terms of the values assigned to the National Reference Standards—the *legal* units. It is only rarely that one needs also to state accuracy in terms of the defined SI unit by taking into account the uncertainty in the assignment of the National Reference Standard.

General precautions should be observed in electrical measurements, and sources of error should be avoided, as detailed below:

1. The accuracy limits of the instruments, standards, and methods used should be known so that appropriate choice of these measuring elements may be made. It should be noted that instrument *accuracy classes* state the “initial” accuracy. Operation of an instrument, with energy applied over a prolonged period, may cause errors due to elastic fatigue of control springs or resistance changes in instrument elements because of heating under load. ANSI C39.1 specifies permissible limits of error of portable instruments because of sustained operation.
2. In any other than rough determinations, the *average of several readings* is better than one. Moreover, the alteration of measurement conditions or techniques, where feasible, may help to avoid or minimize the effects of accidental and systematic errors.
3. The *range* of the measuring instrument should be such that the measured quantity produces a reading large enough to yield the desired precision. The deflection of a measuring instrument should preferably exceed half scale. Voltage transformers, wattmeters, and watthour meters should be operated near to rated voltage for best performance. Care should be taken to avoid either momentary or sustained overloads.
4. *Magnetic fields*, produced by currents in conductors or by various classes of electrical machinery or apparatus, may combine with the fields of portable instruments to produce errors. Alternating or time-varying fields may induce emfs in loops formed in connections or the internal wiring of bridges, potentiometers, etc. to produce an error signal or even “electrical noise” that may obscure the desired reading. The effects of stray alternating fields on ac indicating instruments may be eliminated generally by using the average of readings taken with direct and reversed connections; with direct fields and dc instruments, the second reading (to be averaged with the first) may be taken after rotating the instrument through 180°. If instruments are to be mounted in magnetic panels, they should be calibrated in a panel of the same material and thickness. It also should be noted that Zener-diode-based references are affected by magnetic fields. This may alter the performance of digital meters.
5. In measurements involving high resistances and small currents, *leakage paths* across insulating components of the measuring arrangement should be eliminated if they shunt portions of the measuring circuit. This is done by providing a guard circuit to intercept current in such shunt paths or to keep points at the same potential between which there might otherwise be improper currents.
6. Variations in *ambient temperature* or internal temperature rise from self-heating under load may cause errors in instrument indications. If the temperature coefficient and the instrument temperature are known, readings can be corrected where precision requirements justify it. Where measurements involve extremely small potential differences, thermal emfs resulting from temperature differences between junctions of dissimilar metals may produce errors; heat from the observer’s hand or heat generated by the friction of a sliding contact may cause such effects.
7. *Phase-defect angles* in resistors, inductors, or capacitors and in instruments and instrument transformers must be taken into account in many ac measurements.
8. Large *potential differences* are to be avoided between the windings of an instrument or between its windings and frame. Electrostatic forces may produce reading errors, and very large potential

difference may result in insulating breakdown. Instruments should be connected in the ground leg of a circuit where feasible. The moving-coil end of the voltage circuit of a wattmeter should be connected to the same line as the current coil. When an instrument must be at a high potential, its case must be adequately insulated from ground and connected to the line in which the instrument circuit is connected, or the instrument should be enclosed in a screen that is connected to the line. Such an arrangement may involve shock hazard to the operator, and proper safety precautions must be taken.

9. *Electrostatic charges* and consequent disturbance to readings may result from rubbing the insulating case or window of an instrument with a dry dustcloth; such charges can generally be dissipated by breathing on the case or window. Low-level measurements in very dry weather may be seriously affected by charges on the clothing of the observer; some of the synthetic textile fibers—such as nylon and Dacron—are particularly strong sources of charge; the only effective remedy is the complete screening of the instrument on which charges are induced.
10. *Position influence* (resulting from mechanical unbalance) may affect the reading of an analog-type indicating instrument if it is used in a position other than that in which it was calibrated. Portable instruments of the better accuracy classes (with antiparallax mirrors) are normally intended to be used with the axis of the moving system vertical, and the calibration is generally made with the instrument in this position.

3.1.2 Detectors and Galvanometers

Detectors are used to indicate approach to balance in bridge or potentiometer networks. They are generally responsive to small currents or voltages, and their sensitivity—the value of current or voltage that will produce an observable indication—ultimately limits the resolution of the network as a means for measuring some electrical quantity.

Galvanometers are deflecting instruments which are used, mainly, to *detect* the presence of a small electrical quantity—current, voltage, or charge—but which are also used in some instances to measure the quantity through the magnitude of the deflection.

The D'Arsonval (moving-coil) galvanometer consists of a coil of fine wire suspended between the poles of a permanent magnet. The coil is usually suspended from a flat metal strip which both conducts current to it and provides control torque directed toward its neutral (zero-current) position. Current may be conducted from the coil by a helix of fine wire which contributes very little to the control torque (pendulous suspension) or by a second flat metal strip which contributes significantly to the control torque (taut-band suspension). An iron core is usually mounted in the central space enclosed by the coil, and the pole pieces of the magnet are shaped to produce a uniform radial field throughout the space in which the coil moves. A mirror attached to the coil is used in conjunction with a lamp and scale or a telescope and scale to indicate coil position.

The pendulous-suspension type of galvanometer has the advantage of higher sensitivity (weaker control torque) for a suspension of given dimensions and material and the disadvantage of responsiveness to mechanical disturbances to its supporting platform, which produce anomalous motions of the coil. The taut-suspension type is generally less sensitive (stiffer control torque) but may be made much less responsive to mechanical disturbances if it is properly balanced, that is, if the center of mass of the moving system is in the axis of rotation determined by the taut upper and lower suspensions.

Galvanometer sensitivity can be expressed in a number of ways, depending on application:

1. The *current* constant is the current in microamperes that will produce unit deflection on the scale—usually a deflection of 1 mm on a scale 1 m distant from the galvanometer mirror.
2. The *megohm* constant is the number of megohms in series with the galvanometer through which 1 V will produce unit deflection. It is the reciprocal of the current constant.
3. The *voltage* constant is the number of microvolts which, in a critically damped circuit (or another specified damping), will produce unit deflection.

4. The *coulomb* constant is the charge in microcoulombs which, at a specified damping, will produce unit ballistic throw.
5. The *flux-linkage* constant is the product of change of induction and turns of the linking search coil which will produce unit ballistic throw.

All these sensitivities (galvanometer response characteristics) can be expressed in terms of current sensitivity, circuit resistance in which the galvanometer operates, relative damping, and period. If we define *current* sensitivity S_i as deflection per unit current, then—in appropriate units—the *voltage* sensitivity (the deflection per unit voltage) is

$$S_e = \frac{S_i}{R}$$

where R is the resistance of the circuit, including the resistance of the galvanometer coil. The *coulomb* sensitivity is

$$\frac{\theta}{Q} = \frac{2\pi}{T_o} S_i \exp\left(\frac{-\gamma}{\sqrt{1-\gamma^2}} \tan^{-1} \frac{\sqrt{1-\gamma^2}}{\gamma}\right)$$

where T_o is the undamped period and γ is the relative damping in the operating circuit. The *flux-linkage* sensitivity is

$$\frac{\theta}{\int e dt} \approx S_i \frac{2\pi}{T_o} \frac{1}{2R_c} \frac{1}{1-\gamma_0}$$

for the case of greatest interest—maximum ballistic response—where the galvanometer is heavily overdamped, γ_0 being the open-circuit relative damping, $\int e dt$ the time integral of induced voltage or the change in flux linkages in the circuit, and R_c the circuit resistance (including that of the galvanometer) for which the galvanometer is critically damped.

Galvanometer motion is described by the differential equation

$$P\ddot{\theta} + \left(K + \frac{G^2}{R}\right)\dot{\theta} + U\theta = \frac{GE}{R}$$

where θ is the angle of deflection in radians, P is the moment of inertia, K is the mechanical damping coefficient, G is the motor constant ($G = \text{coil area turns} \times \text{air-gap field}$), R is total circuit resistance (including the galvanometer), and U is the suspension stiffness. If the viscous and circuital damping are combined,

$$K + G^2/R = A$$

the roots of the auxiliary equation are

$$m = \frac{A}{2P} \pm \sqrt{\frac{A^2}{4P^2} - \frac{U}{P}}$$

Three types of motion can be distinguished.

1. *Critically damped* motion occurs when $A^2/4P^2 = U/P$. It is an aperiodic, or deadbeat, motion in which the moving system approaches its equilibrium position without passing through it in the shortest time of any possible aperiodic motion. This motion is described by the equation

$$y = 1 - \left(1 + \frac{2\pi t}{T_o}\right) \exp\left(\frac{-2\pi t}{T_o}\right)$$

where y is the fraction of equilibrium deflection at time t and T_o is the undamped period of the galvanometer—the period that the galvanometer would have if $A = 0$. If the total damping coefficient

at critical damping is A_c , we can define relative damping as the ratio of the damping coefficient A for a specific circuit resistance to the value A_c it has for critical damping— $\gamma = A/A_c$, which is unity for critically damped motion.

2. In *overdamped* motion, the moving system approaches its equilibrium position without overshoot and more slowly than in critically damped motion. This occurs when

$$\frac{A^2}{4P^2} > \frac{U}{P}$$

and $\gamma > 1$. For this case, the motion is described by the equation

$$y = 1 - \left(\frac{\gamma}{\sqrt{\gamma^2 - 1}} \sinh \frac{2\pi t}{T_o} \sqrt{\gamma^2 - 1} + \cosh \frac{2\pi t}{T_o} \sqrt{\gamma^2 - 1} \right) \exp \left(\frac{-2\pi t}{T_o} \gamma \right)$$

3. In *underdamped* motion, the equilibrium position is approached through a series of diminishing oscillations, their decay being exponential. This occurs when

$$\frac{A^2}{4P^2} < \frac{U}{P}$$

and $\gamma < 1$. For this case, the motion is described by the equation

$$y = 1 - \frac{1}{\sqrt{1 - \gamma^2}} \left[\sin \left(\frac{2\pi t}{T_o} \sqrt{1 - \gamma^2} + \sin^{-1} \sqrt{1 - \gamma^2} \right) \right] \exp \left(\frac{-2\pi t}{T_o} \gamma \right)$$

Damping factor is the ratio of deviations of the moving system from its equilibrium position in successive swings. More conveniently, it is the ratio of the equilibrium deflection to the “overshoot” of the first swing past the equilibrium position, or

$$F = \frac{\theta_1 - \theta_F}{\theta_F - \theta_2} = \frac{\theta_F}{\theta_1 - \theta_F}$$

where θ_F is the equilibrium deflection and θ_1 and θ_2 are the first maximum and minimum deflections of the damped system. It can be shown that damping factor is connected to relative damping by the equation

$$F = \exp \left(\frac{\pi \gamma}{\sqrt{1 - \gamma^2}} \right)$$

The *logarithmic decrement* of a damped harmonic motion is the naperian logarithm of the ratio of successive swings of the oscillating system. It is expressed by the equation

$$\ln \frac{\theta_1 - \theta_F}{\theta_F - \theta_2} = \ln \frac{\theta_F}{\theta_1 - \theta_F} = \lambda$$

and in terms of relative damping

$$\lambda = \frac{\pi \gamma}{\sqrt{1 - \gamma^2}}$$

The *period* of a galvanometer (and, generally, of any damped harmonic oscillator) can be stated in terms of its undamped period T_o and its relative damping γ as $T = T_o / \sqrt{1 - \gamma^2}$.

Reading time is the time required, after a change in the quantity measured, for the indication to come and remain within a specified percentage of its final value. Minimum reading time depends on the relative damping and on the required accuracy (Table 3-1). Thus, for a reading within 1% of equilibrium value, minimum time will be required at a relative damping of $\gamma = 0.83$. Generally in indicating instruments, this is known as *response time* when the specified accuracy is the stated accuracy limit of the instrument.

TABLE 3-1 Minimum Reading Time for Various Accuracies

Accuracy, percent	Relative damping	Reading time/free period
10	0.6	0.37
1	0.83	0.67
0.1	0.91	1.0

External critical damping resistance (CDRX) is the external resistance connected across the galvanometer terminals that produces critical damping ($\gamma = 1$).

Measurement of damping and its relation to circuit resistance can be accomplished by a simple procedure in the circuit of Fig. 3-1. Let R_a be very large (say, 150 k Ω) and R_b small (say, 1 Ω) so that when E is a 1.5-V dry cell, the driving voltage in the local galvanometer loop is a few microvolts (say, 10 μ V). Since circuit damping is related to *total* circuit resistance ($R_c + R_b + R_g$), the galvanometer resistance R_g must be determined first. If R_c is adjusted to a value that gives a convenient deflection and then to a new value R'_c for which the deflection is cut in half, we have $R_g = R'_c - 2R_c - R_b$. Now, let R_c be set at such a value that when the switch is closed, the overshoot is readily observed. After noting the open-circuit deflection θ_o , the switch is closed and the peak value θ , of the first overswing, and the final deflection θ_F are noted. Then

$$\ln \frac{\theta_F - \theta_o}{\theta_1 - \theta_o} = \frac{\pi \gamma_1}{\sqrt{1 - \gamma_1^2}}$$

γ_1 being the relative damping corresponding to the circuit resistance $R_1 = R_g + R_b + R_c$. The switch is now opened, and the first overswing θ_2 past the open-circuit equilibrium position θ_o is noted. Then

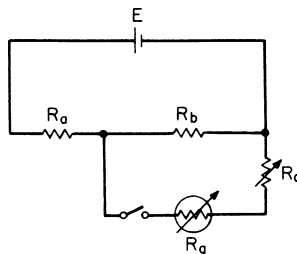
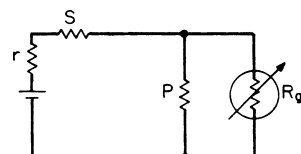
$$\ln \frac{\theta_F - \theta_o}{\theta_2 - \theta_o} = \frac{\pi \gamma_o}{\sqrt{1 - \gamma_o^2}}$$

γ_o being the open-circuit relative damping. The relative damping γ_x for any circuit resistance R_x is given by the relation

$$\frac{R_x}{R_1} = \frac{\gamma_1 - \gamma_o}{\gamma_x - \gamma_o}$$

where it should be noted that the galvanometer resistance R_g is included in both R_x and R_1 . For critical damping R_d can be computed by setting $\gamma_x = 1$, and the external critical damping resistance $CDRX = R_d - R_g$.

Galvanometer shunts are used to reduce the response of the galvanometer to a signal. However, in any sensitivity-reduction network, it is important that relative damping be preserved for proper operation. This can always be achieved by a suitable combination of series and parallel resistance. In Fig. 3-2, let r be the external circuit resistance and R_g the galvanometer resistance such that $r + R_g$ gives an acceptable damping (e.g., $\gamma = 0.8$) at maximum sensitivity. This damping will be preserved when the sensitivity-reduction network (S, P) is inserted, if $S = (n - 1)r$ and $P = nr/(n - 1)$, n being the factor by which response is to be reduced. The Ayrton-Mather shunt, shown

**FIGURE 3-1** Determination of relative damping.**FIGURE 3-2** Galvanometer shunt.

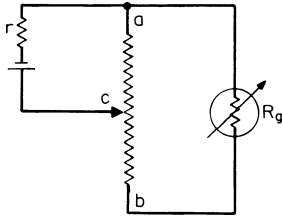


FIGURE 3-3 Ayrton-Mather universal shunt.

in Fig. 3-3, may be used where the circuit resistance r is so high that it exerts no appreciable damping on the galvanometer. R_{ab} should be such that correct damping is achieved by $R_{ab} + R_g$. In this network, sensitivity reduction is

$$n = R_{ac}/R_{ab}$$

and the ratio of galvanometer current I_g to line current I is

$$\frac{I_g}{I} = \frac{R_{ab}}{n(R_g + R_{ab})}$$

The *ultimate resolution* of a detection system is the magnitude of the signal it can discriminate against the noise background present. In the absence of other noise sources, this limit is set by the *Johnson noise* generated by electron thermal agitation in the resistance of the circuit. This is expressed by the formula $e = \sqrt{4k\theta Rf}$, where e is the rms noise voltage developed across the resistance R , k is Boltzmann's constant 1.4×10^{-23} J/K, θ is the absolute temperature of the resistor in kelvin, and f is the bandwidth over which the noise voltage is observed. At room temperature (300 K) and with the assumption that the peak-to-peak voltage is $5 \times$ rms value, the peak-to-peak Johnson noise voltage is $6.5 \times 10^{-10} \sqrt{Rf}$ V. If, in a dc system, we use the approximation that $f = 1/3t$, where t is the system's response time, the Johnson voltage is $4 \times 10^{-10} \sqrt{R/t}$ V (peak to peak).

By using reasonable approximations, it can be shown that the random brownian-motion deflections of the moving system of a galvanometer, arising from impulses by the molecules in the air around it, are equivalent to a voltage indication $e = 5 \times 10^{-10} \sqrt{R/t}$ V (peak to peak), where R is circuit resistance and T is the galvanometer period in seconds. If the galvanometer damping is such that its response time is $t = 2T/3$ (for $\gamma \approx 0.8$), the Johnson noise voltage to which it responds is about $5 \times 10^{-10} \sqrt{R/t}$ V (peak to peak). This value represents the limiting resolution of a galvanometer, since its response to smaller signals would be obscured by the random excursions of its moving system. Thus, a galvanometer with a 4-s-period would have a limiting resolution of about 2 nV in a 100- Ω circuit and 1 nV in a 25- Ω circuit.

It is not surprising that one arrives at the same value from considerations either of random electron motions in the conductors of the measuring circuit or of molecular motions in the fluid that surrounds the system. The resulting figure rests on the premise that the law of equipartition of energy applies to the measuring system and that the galvanometer coil—a body with one degree of freedom—is statically in thermal equilibrium with its surroundings.

Optical systems used with galvanometers and other indicating instruments avoid the necessity for a mechanical pointer and thus permit smaller, simpler balancing arrangements because the mirror attached to the moving system can be symmetrically disposed close to the axis of rotation. In portable instruments, the entire system—source, lenses, mirror, scale—is generally integral with the instrument, and the optical “pointer” may be folded one or more times by fixed mirrors so that it is actually much longer than the mechanical dimensions of the instrument case. In some instances, the angular displacement may be magnified by use of a cylindrical lens or mirror. For a wall- or bracket-mounted galvanometer, the lamp and scale arrangement is external, and the length of the light-beam pointer can be controlled. Whatever the arrangement, the pointer length cannot be indefinitely extended with consequent increase in resolution at the scale. The optical resolution of such a system is, in any event, limited by image diffraction, and this limit—for a system limited by a circular aperture—is $\alpha \approx 1.2\lambda/nd$, where α is the angle subtended by resolvable points, λ is the wavelength of the light, n is the index of refraction of the image space, and d is the aperture diameter. In this case, d is the diameter of the moving-system mirror, and $n = 1$ for air. If we assume that points 0.1 mm apart can just be resolved by the eye at normal reading distance, the resolution limit is reached at a scale distance of about 2 m in a system with a 1-cm mirror, which uses no optical magnification. Thus, for the usual galvanometer, there is no profit in using a mirror-scale separation greater than 2 m. Since resolution is a matter of subtended angle, the corresponding scale distance is proportionately less for systems that make use of magnification.

The *photoelectric galvanometer amplifier* is a detector system in which the light beam from the moving-system mirror is split between two photovoltaic cells connected in opposition, as shown

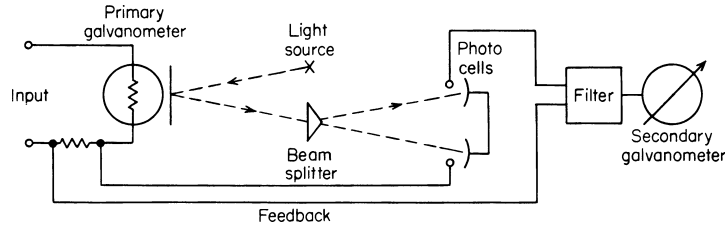


FIGURE 3-4 Photoelectric galvanometer amplifier.

in Fig. 3-4. As the mirror of the primary galvanometer turns in response to an input signal, the light flux is increased on one of the photocells and decreased on the other, resulting in a current and thence an enhanced signal in the circuit of the secondary (reading) galvanometer. Since the photocells respond to the total light flux on their sensitive elements, the system is not subject to resolution limitation by diffraction as is the human eye, and the ultimate resolution of the primary instrument—limited only by its brownian motion and the Johnson noise of the input circuit—may be realized.

Electronic instruments for low-level dc signal detection are more convenient, more rugged, and less susceptible to mechanical disturbances than is a galvanometer. However, considerable filtering, shielding, and guarding must be used to minimize electrical interference and noise. On the other hand, a galvanometer is an extremely efficient low-pass filter, and when operated to make optimal use of its design characteristics, it is still the most sensitive low-level dc detector. Electronic detectors generally make use of either a mechanical or a transistor chopper driven by an oscillator whose frequency is chosen to avoid the local power frequency and its harmonics. This modulator converts the dc input signal to ac, which is then amplified, demodulated, and displayed on an analog-type indicating instrument or fed to a recording device or a signal processor.

AC detectors used for balancing bridge networks are usually tuned low-level amplifiers coupled to an appropriate display device. The narrower the passband of the amplifier, the better the signal resolution, since the narrow passband discriminates against noise of random frequency in the input circuit. Adjustable-frequency amplifier-detectors basically incorporate a low-noise preamplifier followed by a high-gain amplifier around which is a tunable feedback loop whose circuit has zero transmission at the selected frequency so that the negative-feedback circuit controls the overall transfer function and acts to suppress signals except at the selected frequency. The amplifier output may be rectified and displayed on a dc indicating instrument, and added resolution is gained by introducing phase selection at the demodulator, since the wanted signal is regular in phase, while interfering noise is generally random. In detectors of this type, in phase and quadrature signals can be displayed separately, permitting independent balancing of bridge components. Further improvement can result from the use of a low-pass filter between the demodulator and the dc indicator such that the signal of selected phase is integrated over an appreciable time interval up to a second or more.

3.1.3 Continuous EMF Measurements

A *standard of emf* may be either an electrochemical system or a Zener-diode-controlled circuit operated under precisely specified conditions. The *Weston standard cell* has a positive electrode of metallic mercury and a negative electrode of cadmium-mercury amalgam (usually about 10% Cd). The *electrolyte* is a saturated solution of cadmium sulfate with an excess of $\text{Cd} \cdot \text{SO}_4 \cdot \frac{8}{3}\text{H}_2\text{O}$ crystals, usually acidified with sulfuric acid (0.04 to 0.08 N). A paste of mercurous sulfate and cadmium sulfate crystals over the mercury electrode is used as a depolarizer. The saturated cell has a substantial temperature coefficient of emf. Vigoureux and Watts of the National Physical Laboratory have given the following formula, applicable to cells with a 10% amalgam:

$$E_t = E_{20} - 39.39 \times 10^{-6}(t - 20) - 0.903 \times 10^{-6}(t - 20)^2 + 0.00660 \\ \times 10^{-6}(t - 20)^3 - 0.000150 \times 10^{-6}(t - 20)^4$$

where t is the temperature in degree Celsius. Since cells are frequently maintained at 28°C, the following equivalent formula is useful:

$$E_t = E_{28} - 52.899 \times 10^{-6}(t - 28) - 0.80265 \times 10^{-6}(t - 28)^2 + 0.001813 \times 10^{-6}(t - 28)^3 - 0.0001497 \times 10^{-6}(t - 28)^4$$

These equations are general and are normally used only to correct cell emfs for small temperature changes, that is, 0.05 K or less. For changes at that level, negligible errors are introduced by making corrections. Standard cells should always be calibrated at their temperature of use (within 0.05 K) if they are to be used at an accuracy of 5 ppm or better.

A group of saturated Weston cells, maintained at a constant temperature in an air bath or a stirred oil bath, is quite generally used as a laboratory reference standard of emf. The bath temperature must be constant within a few thousandths of a degree if the reference emf is to be reliable to a microvolt. It is even more important that temperature gradients in the bath be avoided, since the individual limbs of the cell have very large temperature coefficients (about +315 $\mu\text{V}/^\circ\text{C}$ for the positive limb and -379 $\mu\text{V}/^\circ\text{C}$ for the negative limb—more than -50 $\mu\text{V}/^\circ\text{C}$ for the complete cell—at 28°C). Frequently, two or three groups of cells are used, one as a reference standard which never leaves the laboratory, the others as transport groups which are used for interlaboratory comparisons and for assignment by a standards laboratory.

Precautions in Using Standard Cells

1. The cell should not be exposed to extreme temperatures—below 4°C or above 40°C.
2. Temperature gradients (differences between the cell limbs) should be avoided.
3. Abrupt temperature changes should be avoided—the recovery period after a sudden temperature change may be quite extended; recovery is usually much quicker in an unsaturated than in a saturated cell. Full recovery of saturated cells from a gross temperature change (e.g., from room temperature to a 35°C maintenance temperature) can take up to 3 months. More significantly, some cell emfs have been seen to exhibit a plateau in their response over a 2- to 3-week period within a week or two after the temperature shock is sustained. This plateau can be as much as 5 ppm higher than the final stable value.
4. Current in excess of 100 nA should never be passed through the cell in either direction; actually, one should limit current to 10 nA or less for as short a time as feasible in using the cell as a reference. Cells that have been short-circuited or subjected to excessive charging current drift until chemical equilibrium in the cell is regained over an extended time period—as long as 9 months, depending on the amount of charge involved.

Zener diodes or diode-based devices have replaced chemical cells as voltage references in commercial instruments, such as digital voltmeters and voltage calibrators. Some of these instruments have uncertainties below 10 ppm, instabilities below 5 ppm per month (including drift and random uncertainties), and temperature coefficient of output as low as 2 ppm/°C.

The best devices, as identified in a testing in selection process, are available as solid-state voltage reference or transport standards. Such instruments generally have at least two outputs, one in the range of 1.018 to 1.02 V for use as a standard cell replacement and the other in the range of 6.4 to 10 V, the output voltage of the reference device itself. The lower voltage is usually obtained via a resistive divider.

Other features sometimes include a vernier adjustment for the lower voltage for adjusting to equal the output of a given standard cell and internal batteries for complete isolation. Such devices have performance approaching that of standard cells and can be used in many of the same applications. Some have stabilities (drift rate and random fluctuations) as low as 2 to 3 ppm per year and temperature coefficient of 0.1 ppm/°C.

The current through the reverse-biased junction of a silicon diode remains very small until the bias voltage exceeds a characteristic V_z in magnitude, at which point its resistance becomes abruptly

very low so that the voltage across the junction is little affected by the junction current. Since the voltage-current relationship is repeatable, the diode may be used as a standard of voltage as long as its rated power is not exceeded.

However, since V_f is a function of temperature, single junctions are rarely used as voltage references in precise applications. Since a change in temperature shifts the I - V curve of a junction, the use of a forward-biased junction in series with Zener diode permits a current level to be found at which changes in Zener voltage from temperature changes are compensated by changes in the voltage drop across the forward-biased junction.

Devices using this principle fall into two categories: the temperature-compensated Zener diode, in which two diodes are in series opposition, and the reference amplifier, in which the Zener diode is in series with the base-emitter junction of an appropriate n pn silicon transistor. In each case, the two elements may be on the same substrate for temperature uniformity. In some precision devices, the reference element is in a temperature-controlled oven to permit even greater immunity to temperature fluctuations.

Potentiometers are used for the precise measurement of emf in the range below 1.5 V. This is accomplished by opposing to the unknown emf an equal IR drop. There are two possibilities: either the current is held constant while the resistance across which the IR drop is opposed to the unknown is varied, or current is varied in a fixed resistance to achieve the desired IR drop.

Figure 3-5 shows schematically most of the essential features of a general-purpose constant-current instrument. With the standard-cell dial set to read the emf of the reference standard cell, the potentiometer current I is adjusted until the IR drop across 10 of the coarse-dial steps plus the drop to the set point on the standard-cell dial balances the emf of the reference cell. The correct value of current is indicated by a null reading of the galvanometer in position G_1 . This adjustment permits the potentiometer to be read directly in volts. With the galvanometer in position G_2 , the unknown emf is balanced by varying the opposing IR drop. Resistances used from the *coarse* and *intermediate* dials and the *slide wire* are adjusted until the galvanometer again reads null, and the unknown emf can be read directly from the dial settings. The ratio of the unknown and reference emfs is precisely the ratio as the resistances for the two null adjustments, provided that the current is the same.

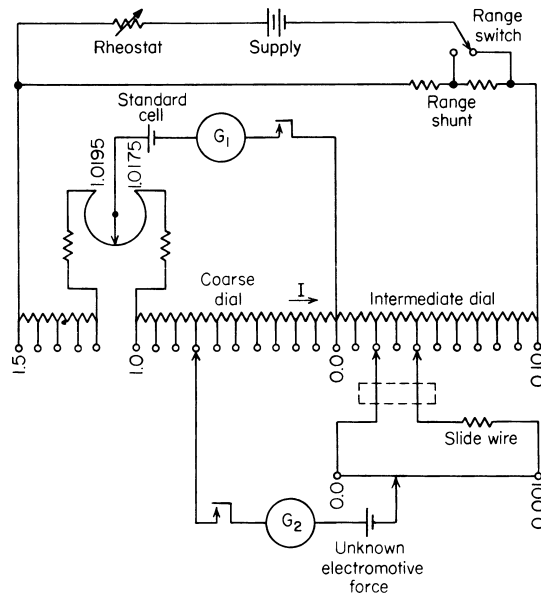


FIGURE 3-5 General purpose constant-current potentiometer.

The switching arrangement is usually such that the galvanometer can be shifted quickly between the G_2 and G_1 positions to check that the current has not drifted from the value at which it was standardized. It will be noted that the contacts of the coarse-dial switch and slide wire are in the galvanometer branch of the circuit. At balance, they carry no current, and their contact resistance does not contribute to the measurement. However, there can be only two noncontributing contact resistances in the network shown; the switch contacts for adjusting the intermediate-dial position do carry current, and their resistance does enter the measurement. Care is taken in construction that the resistances of such current-carrying contacts are low and repeatable, and frequently, as in the example illustrated, the circuit is arranged so that these contributing contacts carry only a fraction of the reference current, and the contribution of their IR drop to the measurement is correspondingly reduced.

Another feature of many general-purpose potentiometers, illustrated in the diagram, is the availability of a reduced range. The resistances of the range shunts have such values that at the 0.1 position of the range-selection switch, only a tenth of the reference current goes through the measuring branch of the circuit, and the range of the potentiometer is correspondingly reduced. Frequently, a $\times 0.01$ range is also available.

In addition to the effect of IR drops at contacts in the measuring circuit, accuracy limits are also imposed by thermal emfs generated at circuit junctions. These limiting factors are increasingly important as potentiometer range is reduced. Thus, in low-range or microvolt potentiometers, special care is taken to keep circuit junctions and contact resistances out of the direct measuring circuit as much as possible, to use thermal shielding, and to arrange the circuit and galvanometer keys so that temperature differences will be minimized between junction points that are directly in the measuring circuit. Generally also, in microvolt potentiometers, the galvanometer is connected to the circuit through a special *thermofree* reversing key so that thermal emfs in the galvanometer can be eliminated from the measurement—the balance point being that which produces zero change in galvanometer deflections on reversal.

An example of the constant-resistance potentiometer is shown in the simplified diagram in Fig. 3-6. It consists basically of a constant-current source, a resistive divider D (used in the current-divider mode), and a fixed resistor R in which the current (and the IR drop) are determined by the setting of the divider. The output of the current source is adjusted by equating the emf of a standard cell to an equal IR drop as shown by the dashed line. This design lends itself to multirange operation by using tap points on the resistor R . Its accuracy depends on the uniformity of the divider, the location of the tap points on R , and the stability of the current source.

Another type of constant-resistance potentiometer, operating from a current comparator which senses and corrects for inequality of ampere-turns in two windings threading a magnetic core, is shown in Fig. 3-7. Two matched toroidal cores wound with an identical number of turns are excited by a fixed-frequency oscillator. The fluxes induced in the cores are equal and oppositely directed, so they cancel with respect to a winding that encloses both. In the absence of additional magnetomotive force (mmf), the detector winding enclosing both cores receives no signal.

If, in another winding A enclosing both cores, we inject a direct current, its mmf reinforces the flux in one core and opposes the other. The net flux in the detector winding induces a voltage in it. This signal is used to control current in another winding B which also threads both cores. When the mmf of B is equal to and opposite that of A , the detector signal is zero and the ampere-turns of A and B are equal. Thus, a constant current in an adjustable number of turns is matched to a variable current in a fixed number of turns, and the voltage drop $I_B R$ is used to oppose the emf to be measured.

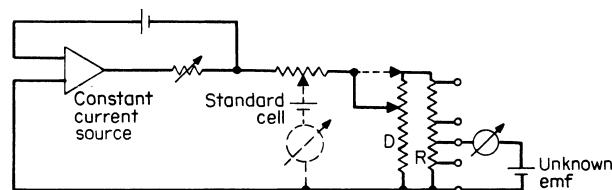


FIGURE 3-6 Constant-resistance potentiometer.

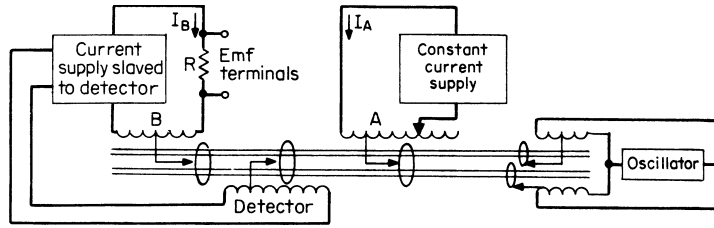


FIGURE 3-7 Current-comparator potentiometer.

The system is made direct-reading in voltage units (in terms of the turns ratio B/A) by adjusting the constant-current source with the aid of a standard-cell circuit (not shown in the figure). This type of potentiometer has an advantage over those whose continuing accuracy depends on the stability of a resistance ratio; the ratio here is the turns ratio of windings on a common core, dependent solely on conductor position and hence not subject to drift with time.

Decade voltage dividers generally use the Kelvin-Varley circuit arrangement shown in Fig. 3-8. It will be seen that two elements of the first decade are shunted by the entire second decade, whose total resistance equals the combined resistance of the shunted steps of decade I. The two sliders of decade I are mechanically coupled and move together, keeping the shunted resistance constant regardless of switch position. Thus, the current divides equally between decade II and the shunted elements of decade I, and the voltage drop in decade II equals the drop in one unshunted step of decade I. The effect of contact resistance at the switch points is somewhat diminished because of the division of current. The Kelvin-Varley principle is used in succeeding decades except the final one, which has only a single switch contact. Such voltage dividers may have as many as eight decades and have ratio accuracies approaching 1 part in 10^6 of input.

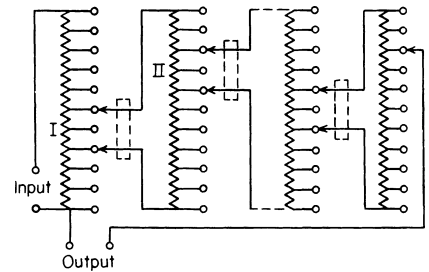


FIGURE 3-8 Decade voltage divider.

Spark gaps provide a means of measuring high voltages. The maximum gap which a given voltage will break down depends on air density, gap geometry, crest value of the voltage, and other factors (see Sec. 27). Sphere gaps constitute a recognized means for measuring crest values of alternating voltages and of impulse voltages. IEEE Standard 4 has tables of sparkover voltages for spheres ranging from 6.25 to 200 cm in diameter and for voltages from 17 to 2500 kV. Sphere gap voltage tables are also available in ANSI Standard 68.1 and in IEC Publication 52.

3.1.4 Continuous Current Measurements

Absolute current measurement relates the value of the current unit—the ampere—to the prototype mechanical units of length, mass, and time—the meter, the kilogram, and the second—through force measurements in an instrument called a *current balance*. Such instruments are to be found generally only in national standards laboratories, which have the responsibility of establishing and maintaining the electrical units. In a current balance, the force between fixed and movable coils is opposed by the gravitational force on a known mass, the balance equation being $I^2(\partial M/\partial X) = mg$. The construction of the coil system is such that the rate of change with displacement of mutual inductance between fixed and moving coils can be computed from measured coil dimensions. Absolute current determinations are used to assign the emf of reference standard cells. A $1\text{-}\Omega$ resistance standard is connected in series with the fixed- and moving-coil system, and its drop is compared with the emf of a cell during the force measurement. Thus, the National Reference Standard of voltage is derived from absolute ampere and ohm determinations.

The *potentiometer method* of measuring continuous currents is commonly used where a value must be more accurate than can be obtained from the reading of an indicating instrument. The current to be measured is passed through a four-terminal resistor (shunt) of known value, and the voltage developed between its potential terminals is measured with a potentiometer. If the current is small so that there is no significant temperature rise in the shunt, the measurement accuracy can be 0.01% or better. In general, the accuracy of potentiometer measurements of continuous currents is limited by how well the shunt resistance is known under operating conditions.

Measurement of very small continuous currents, down to 10^{-17} A, have been accomplished by means of *electrometer tubes*—vacuum tubes designed so that the grid has practically no leakage current either over its insulating supports or to the cathode. The current to be measured flows through a very high resistance (up to $10^{12} \Omega$), and the voltage drop is impressed on the grid of an electrometer tube. The plate current is observed and the voltage drop is duplicated by producing the plate current with a known adjustable voltage. The current can then be calculated from the voltage and resistance.

3.1.5 Analog Instruments

Analog instruments are electromechanical devices in which an electrical quantity is measured by conversion to a mechanical motion. Such instruments can be classified according to the principle on which the instrument operates. The usual types are permanent-magnet moving-coil, moving-iron, dynamometer, and electrostatic. Another grouping is on the basis of use: panel, switchboard, portable, and laboratory-standard. Accuracy also can be the basis of classification. Details concerning performance and other specifications are to be found in ANSI Standard C39.1, Requirements for Electrical Analog Indicating Instruments.

Permanent-magnet moving-coil instruments are the most common type in general use. The operating mechanism consists of a coil of fine wire suspended in such a manner that it can rotate in an annular gap which has a radial magnetic field. The torque, generated by the current in the moving coil reacting to the magnetic field of the gap, is opposed by some form of spring restraint. The restraint may be a helical spring, in which case the coil is supported by a pivot and jewel, or both the support and the angular restraint is by means of a taut-band suspension.

The position which the coil assumes when the torque and spring restraint are balanced is indicated by either a pointer or a light beam on a scale. The scale is calibrated in units suitable to the application: volts, milliamperes, etc. To the extent that the magnetic field is uniform, the spring restraint linear, and the coil positioning symmetrical, the deflection will be linearly proportional to the ampere-turns in the coil.

Because the field of the permanent magnet is unidirectional, reversal of the coil current will reverse the torque so that the instrument will deflect only with direct current in the moving coil. Scales are usually provided with the zero-current position at the left to allow a full-range deflection. However, where measurement is required with either polarity, a zero center scale position is used. The coil is limited in its ability to carry current to 50 or 100 mA.

Rectifiers and thermoelements are used with permanent-magnet moving-coil instruments to provide ac operation. The addition of a rectifier circuit, usually in the form of a bridge, gives an instrument in which the deflection is in terms of the average value of the voltage or current. It is customary to label the scale in terms of 1.11 times the average; this is the correct waveform factor to read the rms value of a sine wave. If the rectifier instrument is used to measure severely nonsinusoidal waveforms, large errors will result. The high sensitivity that can be obtained with the rectifier type of instrument and its reasonable cost make it widely used.

To provide a true rms reading with the permanent-magnet moving-coil instrument, a thermoelement is the usual converter. The current to be measured is fed through a resistance of such value that it will heat appreciably. A thermocouple is placed in intimate thermal contact with the heater resistance, and the output of the couple is used to energize a permanent-magnet moving-coil instrument. The instrument deflection of such a combination is proportional to the square of the current; using a square-root factor in drawing the scale allows it to be read in terms of the rms value of the current. For high-sensitivity use, the thermoelement is placed in an evacuated bulb to eliminate convection heat loss.

The prime advantage of the thermoelement instrument is the high frequency at which it will operate and the rms indication. The upper frequency limit is determined by the skin effect in the heater. Instruments have been built with response to several hundred megahertz. There is one very important limitation to these instruments. The heater must operate at a temperature of 100°C or more to provide adequate current to the movement. Overrange of the current will cause heater temperature to increase as the square of the current. It is possible to burn out the heater with relatively small overloads.

Moving-iron instruments are widely used at power frequencies. The radial-vane moving-iron type operates by current in the coil which surrounds two magnetic vanes, one fixed and one that can rotate in such a manner as to increase the spacing between them. Current in the coil causes the vanes to be similarly magnetized and so to repel each other. The torque produced by the moving vane is proportional to the square of the current and is independent of its polarity.

Figure 3-9 shows two ways in which a wattmeter may be connected to measure power in a load. With the moving coil connected at A, the instrument will read high by the amount of power used by the moving-coil circuit. If connection is made at B, the wattmeter will read high by the power dissipated in the field coils. When using sensitive, low-range meters, it is necessary to correct for this error. Commercial instruments are available for ranges from a fraction of a watt to several hundred watts self-contained. Range extensions are obtained with current and voltage transformers. In specifying wattmeters, it is necessary to state the current and voltage ranges as well as the watt range.

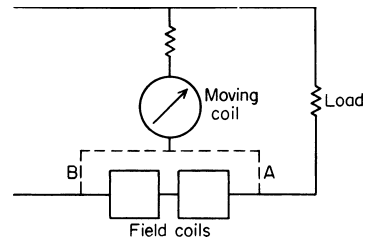


FIGURE 3-9 Alternative wattmeter connections.

Electrostatic voltmeters are actually voltage-operated in contrast to all the other types of analog instruments, which are current-operated. In an electrostatic voltmeter, fixed and movable vanes are so arranged that a voltage between them causes attraction to rotate the movable vane. The torque is proportional to the energy stored in the capacitance, and thus to the voltage squared, permitting rms indication.

Electrostatic instruments are used for voltage measurements where the current drain of other types of instrument cannot be tolerated. Input resistance (due to insulation leakage) amounts to $10^{13} \Omega$ approximately for a range of 100 V (the lowest commercially available) to $3 \times 10^{15} \Omega$ for 100,000-V instruments (the highest commonly available). Capacitance ranges from about 300 pF for the lower ranges to 10 pF for the highest. Multirange instruments in the lower ranges (100 to 5000 V) are frequently made with capacitive dividers which make them inoperable on direct voltage, since the series capacitor blocks out dc. Other multirange instruments use a mechanical movement of the fixed electrode to change ranges. These can be used on dc or ac, as can all single-range voltmeters.

Electronic voltmeters vary widely in performance characteristics and frequency range covered, depending on the circuitry used. A common type uses an initial diode to charge a capacitor. This may be followed by a stabilized amplifier with a microammeter as indicator. Range may be selected by appropriate cathode resistors in the amplifier section. Such instruments normally have very high input impedance (a few picofarads), respond to peak voltage, and are suitable for use to very high frequencies (100 MHz or more). While the response is to *peak* voltage, the scale of the indicating element may be marked in terms of rms for a sine-wave input, that is, $0.707 \times \text{peak voltage}$. Thus, for a nonsinusoidal input, the scale (read as rms volts) may include a serious waveform error, but if the scale reading is multiplied by 1.41, the result is the value of the *peak* voltage.

An alternative network, used in some electronic voltmeters, is an attenuator for range selection, followed by an amplifier and finally a rectifier and microammeter. This system has substantially lower input impedance, and limits of frequency range are fixed by the characteristics of the amplifier. The response in this arrangement may be to *average* value of the input signal, but again, the scale marking may be in terms of rms value for a sine wave. In this case also, the waveform error for nonsinusoidal input must be borne in mind, but if the scale reading is divided by 1.11, the *average* value is obtained. Within these limitations, accuracy may be as good as 1% of full-scale indication in some types of electronic voltmeter, although in many cases a 2 to 5% accuracy may be anticipated.

3.1.6 DC to AC Transfer

General transfer capability is essential to the measurement of voltage, current, power, and energy. The standard cell, the unit of voltage which it preserves, and the unit of current derived from it in combination with a standard of resistance are applicable only to the measurement of dc quantities, while the problems of measurement in the power and communications fields involve alternating voltages and currents. It is only by means of transfer devices that one can assign the values of ac quantities or calibrate ac instruments in terms of the basic dc reference standards. In most instances, the rms value of a voltage or current is required, since the transformation of electrical energy to other forms involves the square of voltages or currents, and the transfer from direct to alternating quantities is made with devices that respond to the square of current or voltage. Three general types of transfer instruments are capable of high-accuracy rms measurements: (1) electrodynamic instruments—which depend on the force between current-carrying conductors; (2) electrothermic instruments—which depend on the heating effect of current; and (3) electrostatic instruments—which depend on the force between electrodes at different potentials. While two of these depend on current and the third on voltage, the use of series and shunt resistors makes all three types available for current or voltage transfer. Traditional American practice has been to use electrodynamic instruments for current and voltage transfer as well as power transfer from direct to alternating current, but recent developments in thermoelements have improved their transfer characteristics until they are now the preferred means for *current* and *voltage* transfer, although the electrodynamic wattmeter is still the instrument of choice for *power* transfer up to 1 kHz.

Electrothermic transfer standards for current and voltage use a thermoelement consisting of a heater and a thermocouple. In its usual form, the heater is a short, straight wire suspended by two supporting lead-in wires in an evacuated glass bulb. One junction of a thermocouple is fastened to its midpoint and is electrically insulated from it with a small bead. The thermal emf—5 to 10 mV at rated current in a conventional element—is a measure of heater current. Multijunction thermoelements having a number of couples in series along the heater also have been used in transfer measurements. Typical output is 100 mV for an input power of 30 mW.

3.1.7 Digital Instruments

Digital voltmeters (DVMs), displaying the measured voltage as a set of numerals, are analog-to-digital converters in which an unknown dc voltage is compared with a stable reference voltage. Internal fixed dividers or amplifiers extend the voltage ranges. For ac measurements, dc DVMs are preceded by ac-to-dc converters. DVMs are widely used as laboratory, portable, and panel instruments because of their convenience, accuracy, and speed. Automatic range changing and polarity indication, freedom from reading errors, and the availability of outputs for data acquisition or control are added advantages. Integrated circuits and modern techniques have greatly increased their reliability and reduced their cost. Full-scale accuracies range from about 0.5% for three-digit panel instruments to 1 ppm for eight-digit laboratory dc voltmeters and 0.016% for ac voltmeters.

Successive-approximation DVMs are automatically operated dc potentiometers. These may be based on resistive voltage or current divider techniques or on dc current comparators. A comparator in a series of steps adjusts a discrete fraction of the reference voltage (by current or voltage division in a resistance network) until it equals the unknown. Various “logic schemes” have been used to accomplish this, and the stepping relays of earlier models have been replaced by electronic or reed switches. Filters reduce input noise (which could prevent a final display) but generally increase the response time. Accuracy depends chiefly on the reference voltage and the ratios of the resistance network.

Voltage-to-frequency-converter (V/f) DVMs generate a ramp voltage at a rate proportional to the input until it equals a fixed voltage, returns the ramp to the starting point, and repeats. The number of pulses (ramps) generated in a fixed time is proportional to the input and is counted and displayed. Since it integrates over the counting time, a V/f DVM has excellent input-noise rejection. The ramp is usually generated by an operational integrator (a high-gain operational amplifier with a capacitor in the feedback loop so that its output is proportional to the integral of the input voltage). The capacitor

is discharged each time by a pulse of constant and opposite charge, and the time interval of the counter is chosen so that the number of pulses makes the DVM direct-reading. Accuracy depends on the integrator and on the charge of the pulse generator, which contains the reference voltage.

Dual-slope DVMs generate a voltage ramp at a rate proportional to the input voltage V_i for a fixed time t_1 . The ramp input is then switched to a reference voltage V_r of the opposite polarity for a time t_2 until the starting level is reached. Pulses with a fixed frequency f are accumulated in a counter, with N_1 counts during t_1 . The counter resets to zero and accumulates N_2 counts during t_2 . Thus, $t_1 = N_1/f$ and $t_2 = N_2/f$.

If the slope of the linear ramp is $m = kV$, the ramp voltage is $V_o = mt = kVt$. Thus $V_i t_1 = V_r t_2$, so $V_i = V_r N_2/N_1$. The time t_1 is controlled by the counter to make N_2 direct-reading in appropriate units. In principle, the accuracy is not dependent on the constants of the ramp generator or the frequency of the pulses. A single operational integrator, switched to either input or reference voltage, generates the ramps. Since there are few critical components, integrated circuits are feasible, leading to simplicity and reliability as well as high accuracy. Because this is an integrating DVM, noise rejection is excellent.

In pulse-width conversion meters, an integrating circuit and matched comparators are used to produce trains of positive and negative pulses whose relative widths are a linear function of any dc input. The difference in positive and negative pulse widths can be measured using counting techniques, and very high resolution and accuracy (up to 1 ppm, relative to an internal voltage reference) can be achieved by integrating the counting over a suitable time period.

Average ac-to-dc converters contain an operational rectifier (an operational amplifier with a rectifier in the feedback circuit), followed by a filter, to obtain the rectified average value of the ac voltage. The operational amplifier greatly reduces errors of nonlinearity and forward voltage drop of the rectifier. For convenience, the output voltage is scaled so that the dc DVM connected to it indicates the rms value of a sine wave. Large errors can result for other waveforms, up to $h/n\%$, with $h\%$ of the n th harmonic in the wave, if n is an odd number. For example, with 3% of third harmonic, the error can be as much as 1%, depending on the phase of the harmonic.

Electronic multipliers and other forms of rms-responding ac-to-dc converters eliminate this waveform error but are generally more complex and expensive. In one version, the feedback rms circuit shown in Fig. 3-10, the two inputs of the multiplier M_1 are connected together so that the instantaneous output of M is v_i^2/V_o . The operational filter $F(RC$ circuit and operational amplifier) makes $V_o = V_i^2/V_o$, where V_i^2 is the square of the rms value. Thus, $V_o = V_i$. The conversion accuracy approaches 0.1% up to 20 kHz in transconductance or logarithmic multipliers, without requiring a wide dynamic range in the instrument, because of the internal feedback. A series of diodes, biased to conduct at different voltage levels, can provide an excellent approximation to a square-law function in a feedback circuit like that of Fig. 3-10.

Specifications for DVMs should follow the recommendations of ANSI Standard C39.7, Requirements for Digital Voltmeters. Accuracy should be stated as the overall limit of error for a specified range of operating conditions. It should be in percent of reading plus percent of full scale and may be different for different frequency and voltage ranges. Accuracy at a narrow range of reference conditions is also often specified for laboratory use. The input configuration (two-terminal, three-terminal unguarded, three- or four-terminal guarded) is important. Number of digits and "over-range" also should be stated.

Errors and Precautions. Because of the sensitivity of DVMs, a number of precautions should be taken to avoid in-circuit errors from ground loops, input noise, etc. The high input impedance of most types makes input loading errors negligible, but this should always be checked. On dc millivolt ranges, unwanted thermal emfs should be checked as well as the normal-mode rejection of ac line-frequency voltage across the input terminals. Two-terminal DVMs (chassis connected to one input as well as to line ground) may measure unwanted voltages from ground currents in the common line.

Errors are greatly reduced in three-terminal DVMs (chassis connected to line ground only) and are generally negligible with guarded four-terminal DVMs (separate guard chassis surrounding the

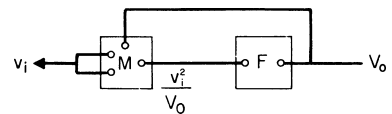


FIGURE 3-10 Electronic rms ac-to-dc converter.

measuring circuit). Such DVMs have very high common-mode rejection. Some types of DVMs introduce small voltage spikes or currents to the measuring circuit, often from internal switching transients, which may cause errors in low-level circuits.

Digital multimeters are DVMs with added circuitry to measure quantities such as dc voltage ratio, dc and ac current, and resistance. Voltage ratio is measured by replacing the reference voltage with one of the unknowns. For current, the voltage across an internal resistor carrying the current is measured by the DVM. For resistance, a fixed reference current is generated and applied to the unknown resistor. The voltage across the resistor is measured by the DVM. Several ranges are provided in each case.

3.1.8 Instrument Transformers

The material that follows is a brief summary of information on instrument transformers as measurement elements. For more extensive information, consult American National Standard C57.13, Requirement for Instrument Transformers; American National Standards Institute; American National Standard C12, Code for Electricity Metering; *Electrical Meterman's Handbook*, Edison Electric Institute; manufacturer's literature; and textbooks on electrical measurements.

AC range extension beyond the reasonable capability of indicating instruments is accomplished with instrument transformers, since the use of heavy-current shunts and high-voltage multipliers would be prohibitive both in cost and power consumption. Instrument transformers are also used to isolate instruments from power lines and to permit instrument circuits to be grounded.

The current circuits of instruments and meters normally have very low impedance, and current transformers must be designed for operation into such a low-impedance secondary burden. The insulation from the primary to secondary of the transformer must be adequate to withstand line-to-ground voltage, since the connected instruments are usually at ground potential. Normal design is for operation with a rated secondary current of 5 A, and the input current may range upward to many thousand amperes. The potential circuits of instruments are of high impedance, and voltage transformers are designed for operation into a high-impedance secondary burden. In the usual design, the rated secondary voltage is 120 V, and instrument transformers have been built for rated primary voltages up to 765 kV.

With the development of higher transmission-line voltages (350 to 765 kV) and intersystem ties at these levels, the coupling-capacitor voltage transformer (CCVT) has come into use for metering purposes to replace the conventional voltage transformer, which, at these voltages, is bulkier and more costly. The metering CCVT, shown in Fig. 3-11, consists of a modular capacitive divider which reduces the line voltage V_1 to a voltage V_2 (10–20 kV), with a series-resonant inductor to tune out the high impedance and make available energy transfer across the divider to operate the voltage transformer which further reduces the voltage to V_M , the metering level. Required metering accuracy may be 0.3% or better.

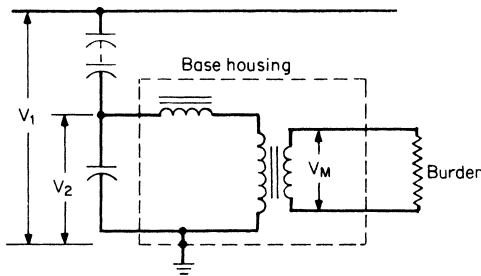


FIGURE 3-11 CCTV metering arrangement.

Instrument transformers are broadly classified in two general types: (1) dry type, having molded insulation (sometimes only varnish-impregnated paper or cloth) usually intended for indoor installation, although large numbers of modern transformers have molded insulation suitable for outdoor operation on circuits up to 15 kV to ground; and (2) liquid-filled types in steel tanks with high-voltage primary terminals, intended for installation on circuits above 15 kV. They are further classified according to accuracy: (1) metering transformers having highest accuracy, usually at relatively low burdens; and (2) relaying and control transformers which in general have higher burden capacity and lower accuracy, particularly at heavy overloads. This accuracy classification is not rigid, since many transformers, often in larger sizes and higher voltage ratings, are suitable for both metering and control purposes.

Another classification differentiates between single and multiple ratios. Multiple primary windings, sometimes arranged for series-parallel connection, tapped primary windings, or tapped secondary windings, are employed to provide multiple ratios in a single piece of equipment. Current transformers are further classified according to their mechanical structure: (1) wound primary, having more than one turn through the core window; (2) through type, wherein the circuit conductor (cable or busbar) is passed through the window; (3) bar type, having a bar, rod, or tube mounted in the window; and (4) bushing type, that is, through type intended for mounting on the insulating bushing of a power transformer or circuit breaker.

Current transformers, whose primary winding is series connected in the line, serve the double purposes of (1) convenient measurement of large currents and (2) insulation of instruments, meters, and relays from high-voltage circuits. Such a transformer has a high-permeability core of relatively small cross section operated normally at a very low flux density. The secondary winding is usually in excess of 100 turns (except for certain small low-burden through-type current transformers used for metering, where the secondary turns may be as low as 40), and the primary is of few turns and may even be a single turn or a section of a bus bar threading the core. The nominal current ratio of such a transformer is the inverse of the turns ratio, but for accurate current measurement, the actual ratio must be determined under loading corresponding to use conditions. For accurate power and energy measurement, the phase angle between the secondary and reversed primary phasor also must be known for the use condition. Insulation of primary from secondary and core must be sufficient to withstand, with a reasonable safety factor, the voltage to ground of the circuit into which it is connected; secondary insulation is much less, since the connected instrument burden is at ground potential or nearly so.

The overload capacity of station-type current transformers and the mechanical strength of the winding and core structure must be high to withstand possible short circuits on the line. Various compensation schemes are used in many transformers to retain ratio accuracy up to several times rated current. The secondary circuit—the current elements of connected instruments or relays—*must never be opened* while the transformer is excited by primary current, because high voltages are induced which may be hazardous to insulation and to personnel and because the accuracy of the transformer may be adversely affected.

Voltage transformers (potential transformers) are connected between the lines whose potential difference is to be determined and are used to step the voltage down (usually to 120 V) and to supply the voltage circuits of the connected instrument burden. Their basic construction is similar to that of a power transformer operating at the same input voltage, except that they are designed for optimal performance with the high-impedance secondary loads of the connected instruments. The core is operated at high flux density, and the insulation must be appropriate to the line-to-ground voltage.

Standard burdens and standard accuracy requirements for instrument transformers are given in American National Standard C57.13 (see Sec. 28).

Accuracy. Most well-designed instrument transformers (provided they have not been damaged or incorrectly used) have sufficient accuracy for metering purposes. See Sec. 10 for typical accuracy curves. Where higher accuracy is required, see Appendix D of ANSI C12, The Code for Electricity Metering.

Another comparison method uses a “standard” transformer of the same nominal rating as the one being tested. Accuracies of 0.01% are attainable. Commercial test sets are available for this work and are widely used in laboratory and field tests. Commercial test sets based on the current-comparator method and capable of 0.001% accuracy are also available. For further details, see ANSI Standard C57.13.

3.1.9 Power Measurement

Electronic wattmeters of 0.1% or better accuracy may be based on a pulse-area principle. Voltages proportional to the applied voltage and to the current (derived from resistors or transformers) govern the height and width of a rectangular pulse so that the area is proportional to the instantaneous power. This is repeated many times during a cycle, and its average represents active power. Average power also can be measured by a system which samples instantaneous voltage and current repeatedly, at predetermined intervals within a cycle. The sampled signals are digitized, and the result is

computed by numerical integration. The response of such a system has been found to agree with that of a standard electrodynamic wattmeter within 0.02% from dc to 1 kHz. Depending on sampling speed, measurements can be made to higher frequencies with somewhat reduced accuracy. In the digital instrument, the multiplication involves discrete numbers and thus has no experimental error except for rounding. Such an arrangement is well-adapted to the measurement of power in situations where current or voltage waveforms are badly distorted.

In the thermal wattmeter, where the arrangement is such that if one current v is proportional to instantaneous load voltage and another i is proportional to load current, their sum is applied to one thermal converter and their difference to another. Assuming identical quadratic response of the converters, their differential output may be represented as

$$V_{dc} = \frac{k}{T} \int_0^T [(v + i)^2 - (v - i)^2] dt = \frac{4k}{T} \int_0^T vi dt$$

which is by definition average power. Multijunction thermal converters with outputs connected differentially are used for the ac-dc transfer of power, with ac and dc current and voltage signals applied simultaneously to both heaters. DC feedback to current input speeds response and maintains thermal balance between heaters, and the output meter becomes a null indicator. This mode of operation can eliminate the requirement for exact quadrature response, and the matching requirement is also eliminated by interchange of the heaters. The Cox and Kusters instrument was designed for operation from 50 to 1000 Hz with ac-dc transfer errors within 30 ppm, and it may be used up to 20 kHz with reduced accuracy. This instrument also is capable of precision measurement with very distorted waveforms.

Laboratory-standard wattmeters use an electrodynamic mechanism and are in the 0.1% accuracy class for dc and for ac up to 133 Hz. This accuracy can be maintained up to 1 kHz or more. Such instruments are shielded from the effects of external magnetic fields by enclosing the coil system in a laminated iron cylinder. Instruments having current ranges to 10 A and voltage ranges to 300 V are generally self-contained. Higher ranges are realized with the aid of precision instrument transformers.

Portable wattmeters are generally of the electrodynamic type. The current element consists of two fixed coils connected in series with the load to be measured. The *voltage element* is a moving coil supported on jewel bearings or suspended by taut bands between the fixed field coils. The moving coil is connected in series with a relatively large noninductive resistor across the load circuit. The coils are mounted in a laminated iron shield to minimize coupling with external magnetic fields. Switchboard wattmeters have the same coil structure but are of broader accuracy class and do not have the temperature compensation, knife-edge pointers, and antiparallax mirrors required for the better-class portable instruments.

Correction for wattmeter power consumption may be important when the power measured is small. When the wattmeter is connected directly to the circuit (without the interposition of instrument transformers), the instrument reading will include the power consumed in the element connected next to the load being measured. If the instrument loss cannot be neglected, it is better to connect the voltage circuit next to the load and include its power consumption rather than that of the current circuit, since it is generally more nearly constant and is more easily calculated. In some low-range wattmeters, designed for use at low-power factors, the loss in the voltage circuit is automatically compensated by carrying the current of the voltage circuit through compensating coils wound over the field coils of the current circuit. In this case, the voltage circuit must be connected next to the load to obtain compensation.

The *inductance error* of a wattmeter may be important at low-power factor. At power factors near unity, the noninductive series resistance in the voltage circuit is large enough to make the effect of the moving-coil inductance negligible at power frequencies, but with low power factor, the phase angle of the voltage circuit may have to be considered. This may be computed as $\alpha = 21.6fL/R$, where α is the phase angle in minutes, f is the frequency in hertz, L is the moving-coil inductance in millihenrys, and R is the total resistance of the voltage circuit in ohms.

A *3-phase 3-wire circuit* requires two wattmeters connected as shown in Fig. 3-12; total power is the algebraic sum of the two readings under all conditions of load and power factor. If the load is balanced, at unity power factor each instrument will read half the load; at 50% power factor one instrument reads all the load and the other reading is zero; at less than 50% power factor one reading will be negative.

Three-phase 4-wire circuits require three wattmeters as shown in Fig. 3-13. Total power is the algebraic sum of the three readings under all conditions of load and power factor. A 3-phase Y system with

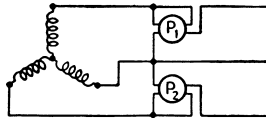


FIGURE 3-12 Power in 3-phase, 3-wire circuit, two wattmeters.

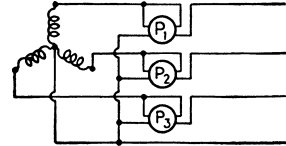


FIGURE 3-13 Power in 3-phase, 4-wire circuit, three wattmeters.

a grounded neutral is the equivalent of a 4-wire system and requires the use of three wattmeters. If the load is balanced, one wattmeter can be used with its current coil in series with one conductor and the voltage circuit connected between that conductor and the neutral. Total power is three times the wattmeter reading in this instance.

Reactive power (reactive voltamperes, or vars) is measured by a wattmeter with its current coils in series with the circuit and the current in its voltage element in quadrature with the circuit voltage.

Corrections for instrument transformers are of two kinds. *Ratio errors*, resulting from deviations of the actual ratio from its nominal, may be obtained from a calibration curve showing true ratio at the instrument burden imposed on the transformer and for the current or voltage of the measurement. The effect of *phase-angle* changes introduced by instrument transformers is modification in the angle between the current in the field coils and the moving coil of the wattmeter; the resulting error depends on the power factor of the circuit and may be positive or negative depending on phase relations, as shown in the table below. If $\cos \theta$ is the *true* power factor in the circuit and $\cos \theta_2$ is the *apparent* power factor (i.e., as determined from the wattmeter reading and the secondary voltamperes), and if K_c and K_v are the true ratios of the current and voltage transformers, respectively, then

$$\text{Main-circuit watts} = K_c K_v \frac{\cos \theta}{\cos \theta_2} \times \text{wattmeter watts}$$

The line power factor $\cos \theta = \cos (\theta_2 \pm \alpha \pm \beta \pm \gamma)$, where θ_2 is the phase angle of the secondary circuit, α is the angle of the wattmeter's voltage circuit, β is the phase angle of the current transformer, and γ is the phase angle of the voltage transformer. These angles— α , β , and γ —are given positive signs when they act to decrease and negative when they act to increase the phase angle between instrument current and voltage with respect to that of the circuit. This is so because a decreased phase angle gives too large a reading and requires a negative correction (and vice versa), as shown in the following table of signs.

Dielectric loss, which occurs in cables and insulating bushings used at high voltages, represents an undesirable absorption of available energy and, more important, a restriction on the capacity of cables and insulating structures used in high-voltage power transmission. The problem of measuring the power consumed in these insulators is quite special, since their power factor is extremely low and the usual wattmeter techniques of power measurement are not applicable. While many methods have been devised over the past half century for the measurement of such losses, the Schering bridge is almost universally the method of choice at the present time. Figure 3-14 shows the basic circuit of the bridge, as described by Schering and Semm in 1920. The balance equations are $C_x = C_s R_1/R_2$ and $\tan \delta_x = \omega R_1 P$, where C_x is the cable or bushing whose losses are to be determined, C_s is a loss-free high-voltage air-dielectric capacitor, R_1 and R_2 are noninductive resistors, and P is an adjustable low-voltage capacitor having negligible loss.

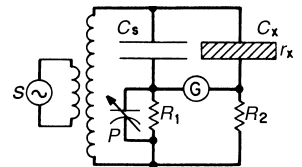


FIGURE 3-14 Schering and Semm's bridge for measuring dielectric loss.

3.1.10 Power-Factor Measurement

The *power factor of a single-phase circuit* is the ratio of the true power in watts, as measured with a wattmeter, to the apparent power in voltamperes, obtained as the product of the voltage and current.

Line power factor	Sign to be used for phase angle					
	α wattmeter		β current transf.		γ voltage transf.	
	Lead*	Lag	Lead	Lag	Lead	Lag
Lead	+	—	—	+	+	—
Lag	—	+	+	—	—	+

*In general, α will be leading only when the inductance of the potential coil has been overcompensated with capacitance.

When the waveform is sinusoidal (and only then), the power factor is also equal to the cosine of the phase angle.

The *power factor of a polyphase circuit* which is balanced is the same as that of the individual phases. When the phases are not balanced, the true power factor is indeterminate. In the wattmeter-voltmeter-ammeter method, the power factor for a balanced 2-phase 3-wire circuit is $P/(\sqrt{2EI})$, where P is total power in watts, E is voltage between outside conductors, and I is current in an outside conductor; for a balanced 3-phase 3-wire circuit, the power factor is $P/(\sqrt{3EI})$, where P is total watts, E is volts between conductors, and I is amperes in a conductor. In the two-wattmeter method, the power factor of a 2-phase 3-wire circuit is obtained from the relation $W_2/W_1 = \tan \theta$, where W_1 is the reading of a wattmeter connected in one phase as in a single-phase circuit and W_2 is the reading of a wattmeter connected with its current coil in series with that of W_1 and its voltage coil across the second phase. At unity power factor, $W_2 = 0$; at 0.707 power factor, $W_2 = W_1$; at lower power factors, $W_2 > W_1$. In a 3-phase 3-wire circuit, power factor can be calculated from the reading of two wattmeters connected in the standard way for measuring power, by using the relation

$$\tan \theta = \frac{\sqrt{3}(W_1 - W_2)}{W_1 + W_2}$$

where W_1 is the larger reading (always positive) and W_2 the smaller.

Power-factor meters, which indicate the power factor of a circuit directly, are made both as portable and as switchboard types. The mechanism of a single-phase electrodynamic meter resembles that of a wattmeter except that the moving system has two coils M , M' . One coil, M , is connected across the line in series with a resistor, whereas M' is connected in series with an inductance. Their currents will be nearly in quadrature. At unity power factor, the reaction with the current-coil field results in maximum torque on M , moving the indicator to the 100 mark on the scale, where torque on M is zero. At zero power factor, M' exerts all the torque and causes the moving system to take a position where the plane of M' is parallel to that of the field coils, and the scale indication is zero. At intermediate power factors, both M and M' contribute torque, and the indication is at an intermediate scale position. In a 2-phase meter, the inductance is not required, coil M being connected through a resistance to one phase, while M' with a resistance is connected to the other phase; the current coil may go in the middle conductor of a 3-wire system. Readings are correct only on a balanced load. In one form of polyphase meter, for balanced circuits, there are three coils in the moving system, connected one across each phase. The moving system takes a position where the resultant of the three torques is minimum, and this depends on power factor. In another form, three stationary coils produce a field which reacts on a moving voltage coil. When the load is unbalanced, neither form is correct.

3.1.11 Energy Measurements

The subject of metering electric power and energy is extensively covered in the American National Standard C21, Code for Electricity Metering, American National Standards Institute. It covers definitions, circuit theory, performance standards for new meters, test methods, and installation standards for watt-hour meters, demand meters, pulse recorders, instrument transformers, and auxiliary devices. Further detailed information may be found in the *Handbook for Electric Metermen*, Edison Electric Institute.

The practical unit of electrical energy is the watt-hour, which is the energy expended in 1 h when the power (or rate of expenditure) is 1 W. Energy is measured in watt-hours (or kilowatt-hours) by

means of a *watthour meter*. A watthour meter is a motor mechanism in which a rotor element revolves at a speed proportional to power flow and drives a registering device on which energy consumption is integrated. Meters for continuous current are usually of the mercury-motor type, whereas those for alternating current utilize the principle of the induction motor.

Polyphase Meter Connections. Obviously, it is extremely important that the various circuits of a polyphase meter be properly connected. If, for example, the current-coil connections are interchanged and the line power factor is 50%, the meter will run at the normal 100% power-factor speed, thus giving an error of 100%.

A test for correct connections is as follows: If the line power factor is over 50%, rotation will always be forward when the potential or the current circuit of either element is disconnected, but in one case the speed will be less than in the other. If the power factor is less than 50%, the rotation in one case will be backward.

When it is not known whether the power factor is less or greater than 50%, this may be determined by disconnecting one element and noting the speed produced by the remaining element. Then change the voltage connection of the remaining element from the middle wire to the other outside wire and again note the speed. If the power factor is over 50%, the speed will be different in the two cases but in the same direction. If the power factor is less than 50%, the rotation will be in opposite directions in the two cases.

When instrument transformers are used, care must be exercised in determining correct connections; if terminals of similar instantaneous polarity have been marked on both current and voltage transformers, these connections can be verified and the usual test made to determine power factor. If the polarities have not been marked, or if the identities of instrument transformer leads have been lost in a conduit, the correct connections can still be established, but the procedure is more lengthy.

Use of Instrument Transformers with Watthour Meters. When the capacity of the circuit is over 200 A, instrument current transformers are generally used to step down the current to 5 A. If the voltage is over 480 V, current transformers are almost invariably employed, irrespective of the magnitude of the current, in order to insulate the meter from the line; in such cases, voltage transformers are also used to reduce the voltage to 120 V. Transformer polarity markings must be observed for correct registration. The ratio and phase-angle errors of these transformers must be taken into account where high accuracy is important, as in the case of a large installation. These errors can be largely compensated for by adjusting the meter speed.

Reactive Voltampere-Hour (Var-Hour) Meters. Reactive voltampere-hour (var-hour) meters are generally ordinary watthour meters in which the current coil is inserted in series with the load in the usual manner while the voltage coil is arranged to receive a voltage in quadrature with the load voltage. In 2-phase circuits, this is easily accomplished by using two meters as in power measurements, with the current coils connected directly in series with those of the “active” meters but with the voltage coils connected across the quadrature phases. Evidently, if the meters are connected to rotate forward for an inductive load, they will rotate backward for capacitive loads. For 3-phase 3-wire circuits and 3-phase 4-wire circuits, phase-shifting transformers are used normally and complex connections result.

Errors of Var-Hour Meters. The 2- and 3-phase arrangements described above give correct values of reactive energy when the voltages and currents are balanced. The 2-phase arrangement still gives correct values for unbalanced currents but will be in error if the voltages are unbalanced. Both 3-phase arrangements give erroneous readings for unbalanced currents or voltages; an autotransformer arrangement usually will show less error for a given condition of unbalance than the simple arrangement with interchanged potential coils.

Total var-hours, or “apparent energy” expended in a load, is of interest to engineers because it determines the heating of generating, transmitting, and distributing equipment and hence their rating and investment cost. The apparent energy may be computed if the power factor is constant, from the observed watthours P and the observed reactive var-hours Q ; thus var-hours = $\sqrt{P^2 + Q^2}$. This method may be greatly in error when the power factor is not constant; the computed value is always too small.

A number of devices have been offered for the direct measurement of the apparent energy. In one class (*a*) are those in which the meter power factor is made more or less equal to the line power factor. This is accomplished automatically (in the Angus meter) by inserting a movable member in the voltage-coil pole structure which shifts the resulting flux as line power factor changes. In others, autotransformers are used with the voltage elements to give a power factor in the meter close to expected line power factor. By using three such pairs of autotransformers and three complete polyphase watt-hour-meter elements operating on a single register, with the record determined by the meter running at the highest speed, an accuracy of about 1% is achieved, with power factors ranging from unity down to 40%. In the other class (*b*), vector addition of active and reactive energies is accomplished either by electromagnetic means or by electromechanical means, many of them very ingenious. But the result obtained with the use of modern watt-hour and var-hour meters are generally adequate for most purposes.

The *accuracy* of a watt-hour meter is the percentage of the total energy passed through a meter which is registered by the dials. The watthours indicated by the meter in a given time are noted, while the actual watts are simultaneously measured with standard instruments. Because of the time required to get an accurate reading from the register, it is customary to count revolutions of the rotating element instead of the register. The accuracy of the gear-train ratio between the rotating element and the first dial of the register can be determined by count. Since the energy represented by one revolution, or the *watthour constant*, has been assigned by the manufacturer and marked on the meter, the indicated watthours will be $K_h \times R$, where K_h is the watthour constant and R the number of revolutions.

Reference Standards. *Reference standards* for dc meter tests in the laboratory may be ammeters and voltmeters, in portable or laboratory-standard types, or potentiometers; in ac meter tests, use is made of indicating wattmeters and a time reference standard such as a stopwatch, clock, or tuning-fork or crystal-controlled oscillator together with an electronic digital counter. A more common reference is a standard watt-hour meter, which is started and stopped automatically by light pulsing through the anticreep holes of the meter under test.

The *portable standard* watt-hour meter (often called *rotating standard*) method of watt-hour-meter testing is most often used because only one observer is required and it is more accurate with fluctuating loads. Rotating standards are watt-hour meters similar to regular meters, except that they are made with extra care, are usually provided with more than one current and one voltage range, and are portable. A pointer, attached directly to the shaft, moves over a dial divided into 100 parts so that fractions of a revolution are easily read. Such a standard meter is used by connecting it to measure the same energy as is being measured by the meter to be tested; the comparison is made by the "switch" method, in which the register only (in dc standards) or the entire moving element (in ac standards) is started at the beginning of a revolution of the meter under test, by means of a suitable switch, and stopped at the end of a given number of revolutions. The accuracy is determined by direct comparison of the number of whole revolutions of the meter under test with the revolutions (whole and fractional) of the standard. Another method of measuring speed of rotation in the laboratory is to use a tiny mirror on the rotating member which reflects a beam of light into a photoelectric cell; the resulting impulses may be recorded on a chronograph or used to define the period of operation of a synchronous electric clock, etc.

Watt-hour meters used with instrument transformers are usually checked as secondary meters; that is, the meter is removed from the transformer secondary circuits (current transformers must first be short-circuited) and checked as a 5-A 120-V meter in the usual manner. The meter accuracy is adjusted so that when the known corrections for ratio and phase-angle errors of the current and potential transformers have been applied, the combined accuracy will be as close to 100% as possible, at all load currents and power factors. An overall check is seldom required both because of the difficulty and because of the decreased accuracy as compared with the secondary check.

General precautions to be observed in testing watt-hour meters are as follows: (1) The test period should always be sufficiently long and a sufficiently large number of independent readings should be taken to ensure the desired accuracy. (2) Capacity of the standards should be so chosen that readings will be taken at reasonably high percentages of their capacity in order to make observational or scale errors as small as possible. (3) Where indicating instruments are used on a fluctuating load, their average deflections should be estimated in such a manner as to include the time of duration of each deflection as well as the magnitude. (4) Instruments should be so connected that neither the

standards nor the meter being tested is measuring the voltage-circuit loss of the other, that the same voltage is impressed on both, and that the same load current passes through both. (5) When the meter under test has not been previously in circuit, sufficient time should be allowed for the temperature of the voltage circuit to become constant. (6) Guard against the effect of stray fields by locating the standards and arranging the temporary test wiring in a judicious manner.

Meter Constants. The following definitions of various meter constants are taken from the Code for Electricity Metering, 6th ed., ANSI C12.

Register constant K_r is the factor by which the register reading must be multiplied in order to provide proper consideration of the register or gear ratio and of the instrument-transformer ratios to obtain the registration in the desired units.

Register ratio R_r is the number of revolutions of the first gear of the register, for one revolution of the first dial pointer.

Watt-hour constant K_h is the registration expressed in watt-hours corresponding to one revolution of the rotor. (When a meter is used with instrument transformers, the watt-hour constant is expressed in terms of primary watt-hours. For a secondary test of such a meter, the constant is the primary watt-hour constant, divided by the product of the nominal ratios of transformation.)

Test current of a watt-hour meter is the current marked on the nameplate by the manufacturer (identified as TA on meters manufactured since 1960) and is the current in amperes which is used as the basis for adjusting and determining the percentage registration of a watt-hour meter at heavy and light loads.

Percentage registration of a meter is the ratio of the actual registration of the meter to the true value of the quantity measured in a given time, expressed as a percentage. Percentage registration is also sometimes referred to as the *accuracy* or *percentage accuracy* of a meter. The value of one revolution having been established by the manufacturer in the design of the meter, meter watt-hours = $K_h \times R$, where K_h is the watt-hour constant and R is the number of revolutions of rotor in S seconds. The corresponding power in meter watts is $P_m = (3600 \times R \times K_h)/S$. Hence, multiplying by 100 to convert to terms of percentage registration (accuracy),

$$\text{Percentage registration} = \frac{K_h \times R \times 3600 \times 100}{PS}$$

where P is true watts. This is the basic formula for watt-hour meters in terms of true watt reference.

Average Percentage Registration (Accuracy) of Watt-hour Meters. The Code for Electricity Metering makes the following statement under the heading, "Methods of Determination":

The percentage registration of a watt-hour meter is, in general, different at light load than at heavy load, and may have still other values at intermediate loads. The determination of the average percentage registration of a watt-hour meter is not a simple matter as it involves the characteristics of the meter and the loading. Various methods are used to determine one figure which represents the average percentage registration, the method being prescribed by commissions in many cases. Two methods of determining the average percentage registration (commonly called "average accuracy" or "final average accuracy") are in common use:

Method 1. Average percentage registration is the weighted average of the percentage registration at light load (LL) and at heavy load (HL), giving the heavy-load registration a weight of 4. By this method:

$$\text{Weighted average percentage registration} = \frac{LL + 4HL}{5}$$

Method 2. Average percentage registration is the average of the percentage registration at light load (LL) and at heavy load (HL). By this method:

$$\text{Average percentage registration} = \frac{LL + HL}{2}$$

In-Service Performance Tests. *In-service performance tests*, as specified in the Code for Electricity Metering, ANSI C12, shall be made in accordance with a *periodic test schedule*, except that self-contained single-phase meters, self-contained polyphase meters, and 3-wire network meters

also may be tested under either of two other systems, provided that all meters are tested under the same system. These systems are the *variable interval plan* and the *statistical sampling plan*.

The chief characteristic of the *periodic-internal system* is that a fixed percentage of the meters in service shall be tested annually. In the test intervals specified below, the word *years* means calendar years. The periods stated are recommended test intervals. There may be situations in which individual meters, groups of meters, or types of meters should be tested more frequently. In addition, because of the complexity of installations using instrument transformers and the importance of large loads, more frequent inspection and test of such installations may be desirable. In general, periodic test schedules should be as follows:

1. Meters with surge-proof magnets and without demand registers or pulse initiators—16 years.
2. Meters without surge-proof magnets and without demand registers or pulse initiators—8 years.

The chief weaknesses of the preceding periodic test schedule are that it fails to recognize the differences in accuracy characteristics of various types of meters as a result of technical advance in meter design and construction, and fails to provide incentives for maintenance and modernization programs.

The *variable interval plan* provides for the division of meters into homogeneous groups and the establishment of a testing rate for each group based on the results of in-service performance tests made on meters longest in service without test. The maximum test rate recommended is 25% per year. The minimum test rate recommended for the testing of a sufficient number of meters to provide adequate data to determine the test rate for the succeeding year. The provisions of the variable interval plan recognize the difference between various meter types and encourage adequate meter maintenance and replacement programs. See Section 8.1.8.5 of ANSI C12 for details of operation of this plan.

The *statistical sampling program* included is purposely not limited to a specific method, since it is recognized that there are many acceptable ways of achieving good results. The general provisions of the statistical sampling program provide for the division of meters into homogeneous groups, the annual selection and testing of a random sample of meters of each group, and the evaluation of the test results. The program provides for accelerated testing, maintenance, or replacement if the analysis of the sample test data indicates that a group of meters does not meet the performance criteria. See Section 8.1.8.6 of ANSI C12 for details of the operation of this program.

Ampere-Hour Meters. Ampere-hour meters measure only electrical quantity, that is, coulombs or ampere-hours, and therefore, where they are used in the measurement of electrical energy, the potential is assumed to remain constant at a “declared” value, and the meter is calibrated or adjusted accordingly.

Ampere-hour or volt-hour meters for alternating current are not practical but ampere-squared-hour or volt-squared-hour meters are readily built in the form of the induction watt-hour meter. Ampere-hours or volt-hours are then obtainable by extracting the square root of the registered quantities.

Maximum-Demand Meters. Some methods of selling energy involve the maximum amount which is taken by the customer in any period of a prescribed length, that is, the maximum demand. Many types of meters for measuring this demand have been developed, but space permits only a brief description of a few. There are two general classes of demand meters in common use: (1) integrated-demand meters and (2) thermal, logarithmic, or lagged-demand meters. Both have the same function, which is to meter energy in such a way that the registered value is a measure of the load as it affects the heating (and therefore the load-carrying capacity) of the electrical equipment.

Integrated-Demand Meters. Integrated-demand meters consist of an integrating meter element (kWh or kvarh) driving a mechanism in which a timing device returns the demand actuator to zero at the end of each timing interval, leaving the maximum demand indicated on a passive pointer, display, or chart, which in turn is manually reset to zero at each reading period, generally 1 month. Such demand mechanisms operate on what is known as the block-interval principle. There are three types of block-interval demand registers: (1) the indicating type, in which the maximum demand obtained between each reading

period is indicated on a scale or numeric display, (2) the cumulative type, in which the accumulated total of maximum demand during the preceding periods is indicated during the period after the device has been reset and before it is again reset, that is, the maximum demand for any one period is equal or proportional to the difference between the accumulated readings before and after reset, and (3) the multiple-pointer form, in which the demand is obtained by reading the position of the multiple pointers relative to their scale markings. The multiple pointers are resettable to zero.

Another form of demand meter, usually in a separate housing from its associated watt-hour meter, is the recording type, in which the demand is transferred as a permanent record onto a tape by printing, punching, or magnetic means or onto a circular or strip chart. A special form of tape recording for demand metering that has come into wide use in recent years is the pulse recorder, in which pulses from a pulse initiator in the watt-hour meter are recorded on magnetic tape or punched paper tape in a form usable for machine translation by digital-data-processing techniques. Advantages of this system are its great flexibility, freedom from the operating difficulties inherent in inked charts, and freedom from many of the personal errors of manual reading and interpretation of charts.

Thermal, Logarithmic, or Lagged-Demand Meters. These are devices in which the indication of the maximum demand is subject to a characteristic time lag by either mechanical or thermal means. The indication is often designed to follow the exponential heating curve of electrical equipment. Such a response, inherent in thermal meters, averages on a logarithmic and continuous basis, which means that more recent loads are heavily weighted but that, as time passes, their effect decreases. The time characteristics for the lagged meter are defined as the nominal time required for 90% of the final indication with a constant load suddenly applied.

Concordance of Demand Meters and Registers. The measurement of demand may be obtained with meters and registers having various operating principles and employing various means of recording or indicating the demand. On a constant load of sufficient duration, accurate demand meters and registers of both classifications will give the same value of maximum demand, within the limits of tolerance specified. On varying loads, the values given by accurate meters and registers of different classifications may differ because of the different underlying principles of the meters themselves. In commercial practice, the demand of an installation or a system is given with acceptable accuracy by the record or indication of any accurate demand meter or register of acceptable type.

3.1.12 Electrical Recording Instruments

Recording instruments are, in many instances, essentially high-torque indicating instruments arranged so that a permanent, continuous record of the indication is made on a chart. They are made for recording all electrical quantities that can be measured with indicating instruments—current, voltage, power, frequency, etc. In general, the same type of electrical mechanism is used—permanent-magnet moving-coil for direct current and moving-iron or dynamometer for alternating current. The indicator is an inking pen or stylus that makes a record on a chart moving under it at constant speed. This requires a higher torque to overcome friction, so the operating power required for a recording instrument is greater than for a simple indicating instrument. Overshoot is generally undesirable, and recording instruments are slightly overdamped, whereas indicating instruments are usually somewhat underdamped. Some recorders use strip charts; graduations along the length of the chart are usually of time intervals, and the graduations across the chart represent the instrument scale. Alternatively, the chart may be circular, with radial graduations for the instrument scale and time markers around the circumference. The chart paper should be well made and glazed to minimize dimensional changes from temperature and humidity. The ink should be in accordance with the maker's specification for the particular paper used so that it is accepted readily and does not run or blot the paper. Chart drives may be electrical or clockwork. In strip charts, perforations along the edges of the paper are engaged by a drive pinion; circular charts are rotated from a central hub.

Potentiometric self-balancing recorders are systems incorporating dc potentiometers, used either alone or with a transducer to measure various quantities.

Transducers include those for voltage, current, power, power factor, frequency, temperature, humidity, steam or water flow, gas velocity, neutron density, and many other applications.

Types of systems are classified according to the means of detecting and correcting electrical unbalance in the potentiometer circuit.

Accuracy on the order of $1/4\%$ may be expected from potentiometer recorders. To maintain this accuracy, the potentiometer is referenced against a standard cell or a reference voltage provided by a Zener diode. This may be performed by the operator pressing a button to give manual standardization whenever desired. A further refinement is to have automatic standardization, in which the operation is initiated by the chart-drive motor at specified intervals.

Range extension of potentiometric recorders upward is by means of shunt or series resistors. Extension below the basic range of the recorder requires preamplifiers.

Measurement of ac quantities requires the use of ac-to-dc transducers, for example, thermocouples, rectifiers, etc.

Alternating-current potentiometer recorders are simpler than the dc types because they require no standardization against a standard cell or Zener reference voltage and ac-to-dc conversion is not required, eliminating the requirement for a vibrator or saturable reactor. The amplifier and motor-control circuits can be the same as in the dc recorder. By far, the greatest application is with ac bridges, where the ac amplifier acts as an unbalance detector. Strain-gage bridges and bridges which employ platinum or nickel resistive elements for narrow-range temperature measurements frequently employ recorders of this type.

Proximity-type recorders use a high-frequency oscillator whose operation is started or stopped by the insertion of a metal vane into a pair of coils. If the vane is mounted on the pointer of an indicating instrument, the oscillator can sense movement between the pointer and a pair of coils fitted to the oscillator. Servo motion of the coils on displacement of the instrument pointer is accomplished by coupling the oscillator output to the input of a servo amplifier which drives the control motor. This gives a graphic record that follows but does not constrain movement of the instrument pointer. In this way, quantities which can operate an indicating instrument can be recorded without using a transducer.

Telemetry is the indicating or recording of a quantity at a distant point. Telemetry is employed in power measurements to show at a central point the power loads at a number of distant stations and often to indicate total power on a single meter, but practically any electrical quantity which is measured can be transmitted, together with a large number of nonelectrical quantities such as levels, positions, and pressures. Telemetry systems may be classified by type: current, voltage, frequency, position, and impulse.

1. In *current* systems, the movement of the primary measuring element calls for a current in the attached control member to balance the torque created by the quantity measured. This balancing current (usually dc) is sent over the transmitting circuit to be indicated and recorded. Totalizing is possible by the addition of such currents from several sources in a common indicator. The receiver may be as much as 50 mi from the transmitter.
2. In *voltage* systems, a voltage balance may be produced through a control-member voltmeter, or a voltage may be generated by thermocouples heated by the quantity to be measured, or produced as an *IR* drop as a result of a current torque balance, or generated by a generator driven at a speed proportional to the measured quantity. These voltages, however produced, are recorded at a distance by a potentiometer recorder. Here, also, the recorder may be 50 mi from the transmitter.
3. A *variable frequency* may be produced for telemetry by causing the primary element to move a capacitor plate in an rf oscillator or to change the speed of a small dc motor driving an alternator. High-frequency systems cannot be used for transmission over many miles.
4. In *position* systems, the movement of the primary element or of a pilot controlled by the primary element is duplicated at a distance. The pilot may be a bridge balancing resistance or reactance, a variable mutual inductance, or a selsyn motor where the position of a rotor relative to a 3-phase stator is reproduced at the receiver end. Satisfactory operation is usually limited to a few miles.
5. The *impulse* type of transmission of measured quantities is represented by the largest number of devices. The number of impulses transmitted in a given time may represent the magnitude of the quantity being measured, and these may be integrated by a notching device or by a clutch, or the duration of the pulse may be governed by the primary element and interpreted at the receiver. If the impulses are transmitted at high frequency, inductance and capacitance effects in the transmitting line limit the distance of satisfactory transmission; systems using dc impulses operate over 50 to 250 mi.

3.1.13 Resistance Measurements

The SI unit of resistance, the ohm, has been determined directly in terms of the mechanical units by *absolute-ohm* experiments performed at the National Bureau of Standards and at national laboratories in other countries. The reactance of an inductor or capacitor of special construction whose value can be computed from its dimensional properties is compared with a resistance at a known frequency. The value of this resistance can then be assigned in absolute (or SI) units, in terms of length and time—the dimensions of the inductor or capacitor and the time interval corresponding to the comparison frequency. These measurements are made with high precision, and it is believed that the assigned value of the National Reference Standards of resistance, maintained at the NIST, differs from its intended *absolute* value by not more than 1 part in 10^6 .

The *National Reference Standard* of resistance is a group of five 1- Ω resistors of special construction, sealed in double-walled enclosures containing dry nitrogen and kept in a constant temperature bath of mineral oil at 25°C at the NIST. To ensure that their values are constant, they are intercompared at least weekly, compared with other standards of differing construction quarterly, and compared with similar groups in other major national laboratories frequently. Absolute experiments to determine their SI values are performed at rather longer intervals because of the complexity of such experiments—a new experiment of this type may require 5 years or more to complete. This reference group serves as the basis for all resistance measurements made in the country.

Resistance standards, used in precise measurements, are made with high-resistivity metal, in the form of wire or strip. Manganin—a copper-nickel-manganese alloy—is generally used in resistance standards because, when properly treated and protected from air and moisture, it has a number of desirable characteristics, including stable value, low temperature coefficient, low thermal emf at junctions with copper, and relatively high resistivity. A copper-nickel-chromium-aluminum alloy, Evanohm, has been used for high-resistance standards, since it has the same desirable characteristics as manganin and a much higher resistivity.

Standards with nominal values exceeding a megohm (a million ohms) are generally of films of metals such as Nichrome, a nickel-chromium alloy, deposited on a glass substrate. Four forms of standard are in general use. The Thomas-type 1- Ω standard is widely used as a primary standard. The Reichsanstalt form was developed in the German National Laboratory; and the NIST form. All three are designed to be used with their current-terminal lugs in mercury cups and are generally suspended in an oil bath to dissipate heat and to hold the temperature constant at a known value during measurements.

The fourth type, in widespread use for secondary references and as a primary standard at the 10,000- Ω level, consists of one or more coils of Evanohm wound on mica cards or cylindrical formers and terminated in binding posts for use on benchtops. The primary standard version of this type of resistor generally has the resistance elements hermetically sealed in an oil-filled container which also contains some type of resistive temperature sensor.

For highest precision, power dissipation must be kept below 0.1 W (calibrations at the NIST are generally performed at 0.01 W), although as much as 1 W can be dissipated in stirred oil with very small changes in value. The maker's recommendations should be followed regarding safe operating current levels. High- and low-resistance standards use different terminal arrangements. In all standards of 1 Ω lower value and standards up to 10,000 Ω intended for use at the part-per-million (ppm) level of accuracy or better, the current and voltage terminals are separated, whereas in other standards they may not be. The four-terminal construction is required to define the resistance to be measured. Connections to the current-carrying circuit range from a few microhms upward and, in a two-terminal construction, would make the resistance value uncertain to the extent that the connection resistance varies. With four-terminal construction, the resistance of the standard can be *exactly* defined as the voltage drop between the voltage terminals for unit current in and out at the current terminals.

Current standards are precision four-terminal resistors used to measure current by measuring the voltage drop between the voltage terminals with current introduced at the current terminals. These standards, designed for use with potentiometers for precision current measurement, correspond in structure to the shunts used with millivoltmeters for current measurement with indicating instruments. Current standards must be designed to dissipate the heat they develop at rated current, with only a small temperature rise. They may be oil- or air-cooled, the latter design having much greater

surface, since heat transfer to still air is much less efficient than to oil. An air-cooled current standard of $20\ \mu\Omega$ resistance and 2000-A capacity, has an accuracy of 0.04%. Very low resistance oil-cooled standards are mounted in individual oil-filled containers provided with copper coils through which cooling water is circulated and with propellers to provide continuous oil motion.

Alternating-current resistors for current measurement require further design consideration. For example, if the resistor is to be used for current-transformer calibration, its ac resistance must be identical with its dc resistance within $1/100\%$ or better, and the voltage difference between its voltage terminals must be in phase with the current through it within a few tenths of a minute. Thin strips or tubes of resistance material are used to limit eddy currents and minimize "skin" effect, the current circuit must be arranged to have small self-inductance, and the leads from the voltage taps to the potential terminals should be arranged so that, as nearly as possible, the mutual inductance between the voltage and current circuits opposes and cancels the effect of the self-inductance of the current circuit. Figure 3-15 shows three types of construction. In (a) a metal strip has been folded into a very narrow U; in (b) the current circuit consists of coaxial tubes soldered together at one end to terminal blocks at the other end; in (c) a straight tube is used as the current circuit, and the potential leads are snugly fitting coaxial tubes soldered to the resistor tube at the desired separation and terminating at the center.

Resistance coils consist of insulated resistance wire wound on a bobbin or winding form, hard-soldered at the ends to copper terminal wires. Metal tubes are widely used as winding form for dc resistors because they dissipate heat more readily than insulating bobbins, but if the resistor is to be used in ac measurements, a ceramic winding form is greatly to be preferred because it contributes less to the phase-defect angle of the resistor. The resistance wire ordinarily is folded into a narrow loop and wound bifilar onto the form to minimize inductance. This construction results in considerable associated capacitance of high-resistance coils, for which the wire is quite long, and an alternative construction is to wind the coil inductively on a thin mica or plastic card. The capacitive effect is greatly reduced, and the inductance is still quite small if the card is thin.

Resistors in which the wire forms the warp of a woven ribbon have lower time constants than either the simple bifilar- or card-wound types. Manganin is the resistance material most generally employed, but Evanohm and similar alloys are beginning to be extensively used for very high resistance coils. Enamel or silk is used to insulate the wire, and the finished coil is ordinarily coated with shellac or varnish to protect the wire from the atmosphere. Such coatings do not completely exclude moisture, and dimensional changes of insulation with humidity will result in small resistance changes, particularly in high resistances where fine wire is used.

Resistance boxes usually have two to four decades of resistance so that with reasonable precision they cover a considerable range of resistance, adjustable in small steps. For convenience of connection, terminals of the individual resistors are brought to copper blocks or studs, which are connected into the circuit by means of plugs or of dial switches using rotary laminated brushes; clean, well-fitted plugs probably have lower resistance than dial switches but are much less convenient to use.

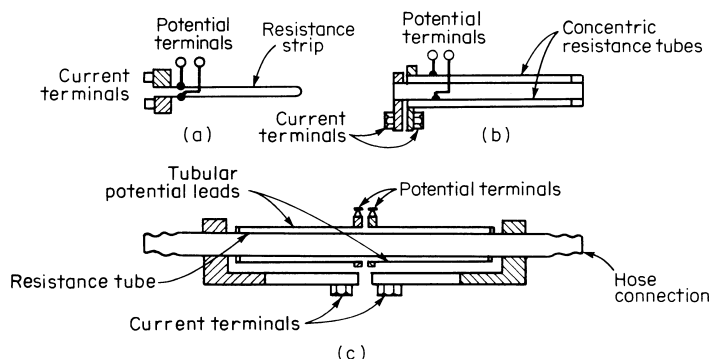


FIGURE 3-15 Types of low-inductance standard resistors.

The residual inductance of decade groups of coils due to switch wiring, and the capacitance of connected but inactive coils, will probably exceed the residuals of the coils themselves, and it is to be expected that the time constant of an assembly of coils in a decade box will be considerably greater than that of the individual coils.

Measurement of resistance is accomplished by a variety of methods, depending on the magnitude of the resistor and the accuracy required. Over the range from a few ohms to a megohm or more, an ohmmeter may be used for an accuracy of a few percent. A simple ohmmeter may consist of a milliammeter, dry cell, and resistor in a series circuit, the instrument scale being marked in resistance units. For a better value, the voltage drop is measured across the resistor for a measured or known current through it. Here, accuracy is limited by the instrument scales unless a potentiometer is used for the current and voltage measurements. The approach is also taken in the wide variety of digital multimeters now in common use. Their manufacturers' specifications indicate a range of accuracies from a few percent to 10 ppm (0.001%) or better from the simplest to the most precise meters. Bridge methods can have the highest accuracy, both because they are null methods in which two or more ratios can be brought to equality and because the measurements can be made by comparison with accurately known standards. For two-terminal resistors, a Wheatstone bridge can be used; for four-terminal measurements, a Kelvin bridge or a current comparator bridge can be used. Bridges for either two- or four-terminal measurements also may be based on resistive dividers. Because of their extremely high input impedance, digital voltmeters may be used with standard resistors in unbalanced bridge circuits of high accuracy.

Digital multimeters are frequently used to make low-power measurements of resistors in the range between a few ohms and a hundred megohms or so. Resolution of such instruments varies from 1% of full scale to a part per million of full scale. These meters generally use a constant-current source with a known current controlled by comparing the voltage drop on an internal "standard" resistor to the emf produced by a Zener diode. The current is set at such a level as to make the meter direct-reading in terms of the displayed voltage; that is, the number displayed by the meter reflects the voltage drop across the resistor, but the decimal point is moved and the scale descriptor is displayed as appropriate. Multimeters typically use three or more fixed currents and several voltage ranges to produce seven or more decade ranges with the full-scale reading from 1.4 to 3.9 times the range. For example, on the 1000- Ω range, full scale may be 3,999.999 Ω . Power dissipated in the measured resistor generally does not exceed 30 mW and reaches that level only in the lowest ranges where resistors are usually designed to handle many times that power. The most accurate multimeters have a resolution of 1 to 10 ppm of range on all ranges above the 10- Ω range. Their sensitivity, linearity, and short-term stability make it possible to compare nominally equal resistors by substitution with an uncertainty 2 to 3 times the least count of the meter. This permits their use in making very accurate measurements, up to 10 ppm, or resistors whose values are close to those of standards at hand. Many less expensive multimeters have only two leads or terminals to use to make measurements. In those cases, the leads from the meter to the resistor to be measured become part of the measured resistance. For low resistances, the lead resistance must be measured and subtracted out, or zeroed out.

The *Wheatstone bridge* is generally used for two-terminal resistors. In the low-resistance range where four-terminal construction is normal, the resistance of connections into the network may be a significant fraction of the total resistance to be measured, and the Wheatstone network is not applicable. Figure 3-16 shows the arrangement of a Wheatstone bridge, where A , B , and C are known resistances, and D is the resistance to be measured. One or more of the known arms is adjusted until the galvanometer G indicates a null; then $D = B(C/A)$. In case D is inductive, the battery switch S_1 should be closed before the galvanometer key S_2 to protect the galvanometer from the initial transient current. In a common form of bridge, B is a decade resistance, adjustable in small steps, while C and A (the ratio arms of the bridge) can be altered to select ratios in powers of 10 from $C/A = 10^{-3}$ to 10^3 . If the value of the unknown resistor is not very different from that of a known resistor, accuracy may be improved by substituting the known and unknown in turn into arm D and noting the difference in

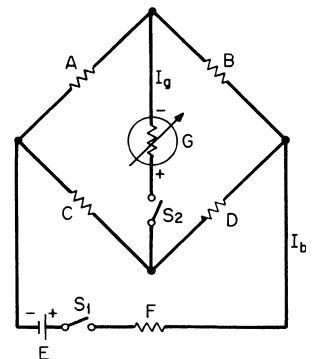


FIGURE 3-16 Wheatstone bridge.

balance readings of the adjustable arm B . Since there has been no change in the ratio arms, any errors they may have do not affect the difference measurement, and only those errors in arm B which were involved in the difference between the settings affect the difference value; in effect, the unknown is measured in terms of a known resistor by a substitution procedure. An alternative form of Wheatstone bridge is frequently assembled from standards and a ratio box of limited range called a *direct-reading ratio set*. This latter has a nominal ratio of unity, with ratio adjustments ranging from 1.005000 to 0.995000, that is, four decades of adjustment, of which the largest has steps of 0.1%. If a balance is made with the two standards in arms B and D and a second balance with the standards interchanged, their difference is half the difference between the balance readings. A similar technique can be used wherever small resistance differences are involved, for example, in the determination of temperature coefficients.

Bridge sensitivity can be determined in the following way. The voltage that would appear in the galvanometer branch of the circuit with switch S_2 open is

$$e = \frac{EBD \Delta B}{(B + D)^2}$$

where E is the supply voltage and ΔB is the amount in proportional parts by which B departs from balance. If, now, the voltage sensitivity of the galvanometer is known for operation in a circuit whose external resistance is that of the bridge as seen from the galvanometer terminals, its response for the unbalance ΔB can be computed. The current in the galvanometer with S_2 closed is

$$I_g = \frac{e}{G + BD/(B + D) + AC/(A + C)}$$

where G is the resistance of the galvanometer. If there is a large current-limiting resistance F in the battery branch of the bridge, the terminal voltage at the AC and BD junction points should be used rather than the supply voltage E in computing e . In connecting and operating a bridge, the allowable power dissipation of its components should first be checked to ensure that these limits are not exceeded, either in any element of the bridge itself or in the resistance to be measured.

Resistive voltage dividers can be used to form bridges for either two- or four-terminal resistance measurements. There are two common forms of resistive voltage divider—the Kelvin-Varley divider and the universal ratio set (URS)—with the former being the most commonly encountered. Each behaves as a potential divider with nearly constant input resistance and an open-circuit output potential of some rational fraction of the input, that fraction being given by the dial settings with calibration corrections applied. In the case of the Kelvin-Varley divider, the maximum ratio is $0.99999 \dots X$, and outputs may be selected with a resolution as great as 1 part in 100 million of the input. Most Kelvin-Varley dividers have input resistances of 10,000 or 100,000 Ω . The URS was specifically designed to calibrate precision potentiometers. Its nominal input resistance is $2111.11 \dots 0 \Omega$, and that is also its full-scale dial designation. Its resolution, or one step of its least-significant dial, is either 1 or 0.1 m Ω . For bridge applications, either divider type appears as two adjacent (series-connected) bridge elements with a ratio of $r/(R - r)$, where r is the dial setting and R is the full-scale dial setting. In a Wheatstone or two-terminal type of bridge as shown in Fig. 3-16, the divider appears as resistors A and B , with C being the known resistor, or standard, and D being the unknown. In that case, the balance equation is

$$D/C = (R - r)/r$$

assuming that the low input of the divider is connected to the node between resistors A and C and its high input to the node between B and D .

Four-terminal applications are more complex, since four separate balances must be made to obtain the ratio between two resistors. The schematic is given in Fig. 3-17. To measure B in terms of A , the lead resistances between node pairs 1–2, 3–4, and 5–6, which we will call x , y , and z , respectively, must be eliminated. This is done by balancing the circuit with the resistor-side detector lead tied to each of the resistor potential leads at the terminals marked p_1 , p_2 , p_3 , and p_4 . The result is

$$\frac{A}{B} = \frac{r_2 - r_1}{r_4 - r_3}$$

where the r s are readings obtained by balancing the divider at each of the potential terminals.

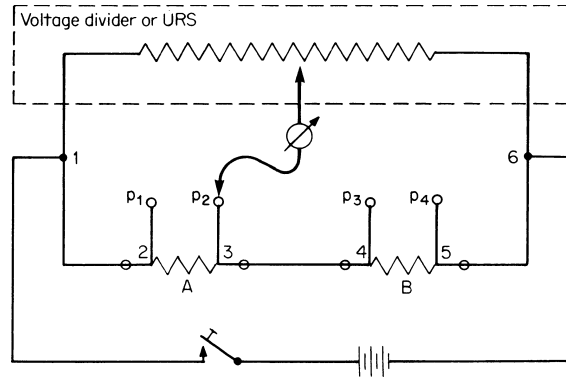


FIGURE 3-17 Four-terminal resistance measurements.

Both types of dividers must be calibrated. This can be done by comparison with a more accurate divider, dial by dial. Such a divider can readily be formed by using a number of nominally equal resistors in series. Each resistor is measured relative to the same standard and the results used to calculate the various ratios in the string of resistors. The string is then used to calibrate each setting of each dial in the voltage divider. In the case of the Kelvin-Varley divider, the dial corrections are interdependent; the correction for the steps in a particular dial depends on the settings of the less-significant dials.

Unbalanced bridge techniques have been made practical by the very high input resistances of modern digital instrumentation and are a satisfactory approach to resistance measurements when the values of the resistors being measured do not differ significantly from one another. They are particularly useful in cases where a process, not expected to change significantly, is being monitored using resistive sensors such as thermistors or copper or nickel resistors. The simplest case is that of a Wheatstone bridge such as that shown in Fig. 3-16. In it, the galvanometer G would be replaced by a digital meter of suitable sensitivity and sufficiently high input impedance to make bridge loading errors insignificant. The bridge relationship then becomes

$$\frac{B}{A + B} + \frac{v}{V} = C + D$$

where V is the voltage applied to the bridge, or $(E - I_b F)$, and v is the reading of the digital meter. In practice, the meter is generally used to measure V as well as v . If the individual elements of the resistor pairs $A - B$ and $C - D$ are nearly equal, the bridge is nearly at balance, v is small, and measurements of v and V need not be made at high accuracies. Resolution is not generally a problem for resistance element values of 100Ω and higher because digital meters with least counts of 0.1 and $1 \mu V$ microvolts are commonly available.

A special form of Wheatstone bridge, known as a *Mueller bridge*, is commonly used for four-terminal measurements of the resistance of platinum resistance thermometers (PRTs). In this bridge, shown in Fig. 3-18, the effects of lead resistance of the PRT are eliminated by including two of the leads in adjacent bridge arms and making a second measurement after transposing the leads. The equations are

$$R_1 + l_1 = R_x + l_4 + S_1 \quad (a)$$

$$R_2 + l_4 = R_x + l_1 + S_2 \quad (b)$$

because the bridge is always used with the ratio arms A and B adjusted to be equal. These two equations may be added to eliminate lead resistances and result in the equation

$$R_x = 0.5 (R_1 - S_1 + R_2 - S_2)$$

where R_1 , S_1 , R_2 , and S_2 are the dial readings (with corrections applied) for conditions A , B .

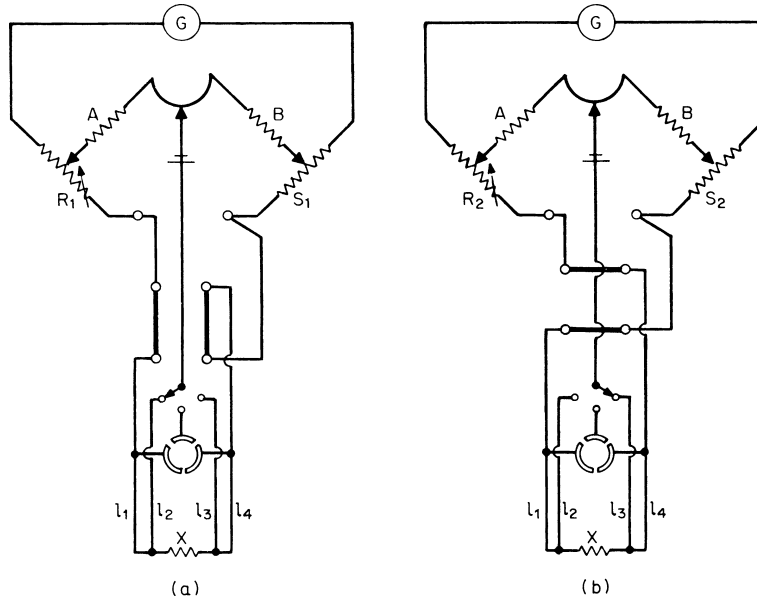


FIGURE 3-18 Mueller bridge.

There is increasing use of low-frequency square- and sinusoidal-wave bridges for PRT measurements. These bridges rely on the inherent ratio stability and accuracy of specially designed transformers and the increased sensitivity available with ac amplifiers to provide accuracies rivaling or surpassing those of the best dc bridges while requiring a minimum amount of upkeep. Both manual and automatic balancing types are available. Many contain one or more resistance reference standards kept at constant temperature in ovens. The transfer accuracies (i.e., accuracy available immediately after the bridge reference resistor has been calibrated) are very nearly equal to their least count, generally 0.1 ppm or better. Such bridges operate at 400 Hz or less to reduce problems with quadrature balances in the resistance being measured and its leads. They usually cover the range below 100 Ω .

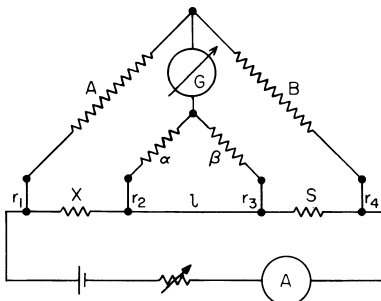


FIGURE 3-19 Kelvin double bridge.

The *Kelvin double bridge* is used for the measurement of low resistances of four-terminal construction, that is, whose current and voltage terminals are separate.

Figure 3-19 shows the network. The balance equation is

$$\frac{X}{S} = \frac{A}{B} + \frac{1}{S} \frac{\beta}{\alpha + \beta + 1} \left(\frac{A}{B} - \frac{\alpha}{\beta} \right)$$

If the resistances X and S being compared are small so that the resistance of the link l connecting them is comparable, the term of the balance equation involving l could be significant, but if the ratio A/B is equal to the ratio α/β , the correction term vanishes. This equality can be demonstrated, after the bridge is balanced, by opening the link l ; if the inner and outer ratios are equal, the bridge will remain balanced. It should be noted that the resistance of the leads r_1, r_2, r_3 , and r_4 between the bridge terminals and the voltage terminals of the resistors may contribute to a ratio unbalance; these lead

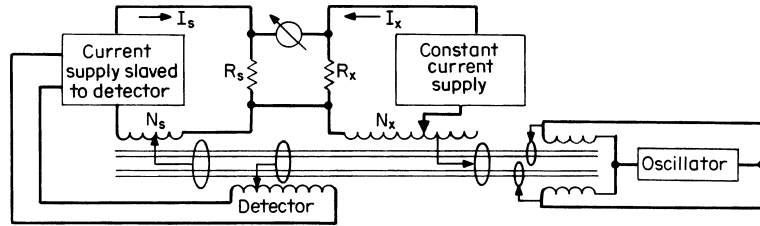


FIGURE 3-20 Current-comparator bridge.

resistances should be in the same ratio as the arms to which they are connected. In some Kelvin bridges, small adjustable resistors are provided for balancing leads; another technique is to shunt the α or β arm with a high resistance until $A/B = \alpha/\beta$ with the link removed. When this balance is achieved, the link l is replaced, and the main bridge balance is readjusted. In some bridges, the outer and inner ratio arms are adjustable only in decimal steps, and the main balance is secured by means of an adjustable standard resistor consisting of a Manganin strip with nine voltage taps of 0.01 or 0.001 Ω each and a Manganin slide wire. Portable bridges may use slide-wire arms and reference resistors to cover a range from 10 $\mu\Omega$ to 10 Ω .

In the *current-comparator bridge*, shown schematically in Fig. 3-20, the ratio of resistor currents is evaluated in the comparator as a balance of ampere-turns in the two circuits. $I_x N_x = I_s N_s$, so $R_x/R_s = N_x/N_s$ when $I_s R_s = I_x R_x$. A resistance determination that depends on the evaluation of a ratio is limited by the stability of that ratio. In Wheatstone and Kelvin bridges, the stability of individual resistors sets that limit; in the current-comparator bridge, the ratio is that of windings on a common magnetic core and therefore stable.

Since this bridge operates in terms of a ratio of currents for equal voltage drops, it can be used to determine power coefficients of low-value resistors. In a Kelvin bridge, the ratio of power dissipated is $P_s/P_x = R_s/R_x$ in the resistors compared; in the comparator bridge, this ratio is $P_s/P_x = R_x/R_s$. Thus, a low-value resistor operated at a substantial power level can be compared directly with a standard of higher resistance operated at a low power level.

Insulation resistance is generally measured by deflection methods. In the case of resistances on the order of a few megohms, a Wheatstone bridge may be used with low to moderate accuracy. A portable megohm bridge is made by General Radio Company. It operates as a Wheatstone bridge with an amplifier and dc indicating instrument as the detector system. A choice of high-resistance ratio arms gives ranges of 0.1 to 10⁴ M Ω . On the highest range, the resolution limit is about 10⁶ M Ω . The deflection methods fall in two general classes: (1) direct-deflection methods and (2) loss-of-charge methods.

Direct-deflection methods (insulation resistance) involve the simple application of Ohm's law. When the resistance is on the order of 1 M Ω , an ordinary voltmeter can give results that are good enough for most purposes. Two readings are taken, one with the voltmeter directly across the source of voltage, the other with the resistance to be measured connected in series with the voltmeter. The resistance is $R = V(d_1 - d_2)/d_2$, where V is the resistance of the voltmeter, d_1 is the voltmeter deflection on the first reading, and d_2 is the deflection on the second reading. The greater the resistance of the voltmeter per volt, the higher is the resistance that can be measured. For higher resistances, a reflecting galvanometer with high current sensitivity is used. Figure 3-21 is a diagram of the arrangement for measuring the insulation resistance of a cable.

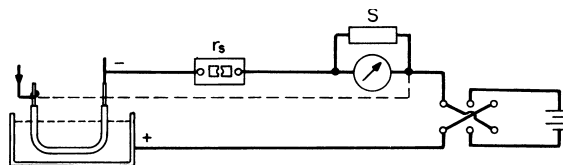


FIGURE 3-21 Diagram for measurement of insulation resistance of cable.

The measurement is made as follows: The galvanometer shunt S is set at the highest shunting value, and the circuit is closed. The shunt is decreased until a large, readable deflection is obtained. The reading is taken 1 min after closing the main switch. This procedure is repeated with only the standard resistor r_s (usually 0.1 or 1 M Ω) in the circuit, the specimen being short-circuited. The resistance of the specimen in megohms is $R = (G/d_1 s_1) - r_s$, where d_1 is the first reading and s_1 the multiplier corresponding to the shunt setting. G , the galvanometer megohm constant, is obtained from the second reading, $G = d r_s s$, where d is deflection, r_s the value of the standard resistor in megohms, and s the shunt multiplier. The conductor is preferably negative to the sheath or water. The standard resistor r_s is left in the circuit as a protection to the galvanometer against accidental short circuit in the sample. The guard for the cable ends is shown by the broken line. Removing braid for several inches at the ends of the sample and dipping the ends in hot paraffin tend to reduce leakage across the face of the insulation from sheath to central conductor, especially in damp weather.

The *loss-of-charge method* of measuring insulation resistance may be used when the resistance is very high, such as the resistance of porcelain and glass and the surface leakage resistance of line insulators. The principle is shown in Fig. 3-22, where the resistance r to be measured is connected in parallel with a capacitor C . Key a is closed and immediately opened, charging the capacitor. Key b is closed immediately after a is opened and the ballistic throw d_1 of the galvanometer noted. The process is repeated, but now a time t s is allowed to pass from the instant of charging before key b is closed and a deflection d_2 observed. The resistance is

$$r = \frac{t}{2.303C \log_{10}(d_1/d_2)} \quad \text{M}\Omega$$

where C is the capacitance in microfarads.

The insulation resistance of the capacitor is not infinite and should be measured in a similar manner with r removed. The two resistances are in parallel, and the corrected value is

$$r = \frac{r_1 r_2}{r_2 - r_1}$$

where r_1 is the resistance value obtained in the first measurement and r_2 is the resistance of the capacitor. For even higher resistance, a growth-of-charge method may be used. In this case, the resistance to be measured is connected in series with a capacitor (preferably an air capacitor), and a known voltage E is applied for t s, the voltage on the capacitor being e at the end of this time. This value, e , is best measured with an electrostatic voltmeter connected continuously across C . The resistance is

$$r = \frac{t}{2.303C \log_{10}[E/(E - e)]} \quad \text{M}\Omega$$

The *resistance of earth connections* may be measured by a three-electrode method. In Fig. 3-23, A is the connection whose resistance to earth is to be measured; it is temporarily disconnected from the distribution system while ground connection is preserved through a connection at D , either temporary or permanent. Two additional "grounds," B and C , are established, separated from each other and from A by not less than 15 ft. These auxiliary grounds may be pieces of metal buried in the earth,

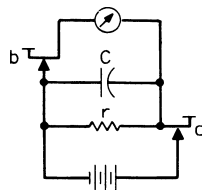


FIGURE 3-22 Leakage method of measuring insulation resistance.

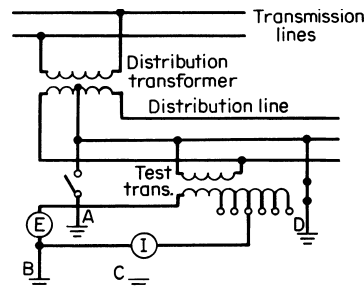


FIGURE 3-23 Resistance of earth connections.

such as a guy wire or a steel pole, making sufficient contact with ground for a good current reading. Resistances between the three electrodes taken in pairs are measured by a voltmeter-ammeter method. These resistances are r_{ab} , r_{bc} , and r_{ac} . Then the resistances are as follows:

$$\text{At } A: \quad R_a = \frac{r_{ab} - r_{bc} + r_{ac}}{2}$$

$$\text{At } B: \quad R_b = \frac{r_{ab} - r_{bc} - r_{ac}}{2}$$

$$\text{At } C: \quad R_c = \frac{r_{bc} - r_{ab} + r_{ac}}{2}$$

The measurement should be made with alternating current, which can be taken from the distribution system through an isolating transformer with secondary taps as shown. A low-range voltmeter is usually required. An Evershed ratio instrument is used for the measurement of ground resistance. One of the moving coils is traversed by the current sent through the ground from the attached hand-operated generator; the other is energized by the voltage drop to an auxiliary, driven electrode.

Faults in electric lines may be divided into two classes, closed- and open-circuit faults. *Closed-circuit faults* consist of *shorts*, where the insulation between conductors becomes faulty, and *grounds*, where the faulty insulation permits the conductor to make contact with the earth. *Open-circuit faults*, or *opens*, are produced by breaks in the conductors.

1. When the short is a low-resistance union of the two conductors, such as at *M* in Fig. 3-24, the resistance should be measured between the ends *AB*; from this value and the resistance per foot of conductor, the distance to the fault can be computed. A measurement of resistance between the other ends *A'B'* will confirm the first computation or will permit the elimination of the resistance in the fault, if this is not negligible.
2. The location of a ground, as at *N* in Fig. 3-24, or of a high-resistance short is made by either of the two classic "loop" methods, provided that a good conductor remains.

Figure 3-25 shows the arrangement of the *Murray loop test*, which is suitable for low-resistance grounds. The faulty conductor and a good conductor are joined together at the far end, and a Wheatstone-bridge arrangement is set up at the near ends with two arms *a* and *b* comprising resistance boxes which can be varied at will; the two segments of line *x* and *y + l* constitute the other two arms; the battery current flows through the ground; the galvanometer is across the near ends of the conductors. At balance,

$$\frac{a}{b} = \frac{x}{y + l} \quad \text{or} \quad \frac{a + b}{b} = \frac{x + y + l}{y + l} \quad \text{ohms}$$

The sum $x + y + l$ may be measured or known. If the conductors are uniform and alike and x and l are expressed as lengths, say, in feet,

$$x = \frac{2al}{a + b} \quad \text{ft}$$

If the ground is of high resistance, very little current will flow through the bridge with the arrangement of Fig. 3-25. In that case, battery and galvanometer should be interchanged, and the galvanometer used should have a high resistance. If ratio arms *a* and *b* consist of a slide wire (preferably with extension coils), the sum $a + b$ is constant and the computation is facilitated. Observations should be taken with direct and reversed currents, especially in work with underground cables.

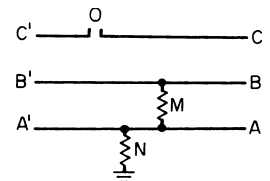


FIGURE 3-24 Line faults.

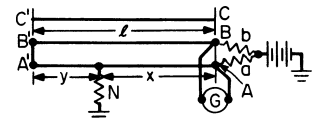


FIGURE 3-25 Murray loop.

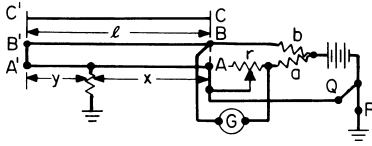


FIGURE 3-26 Varley loop.

In the *Varley loop*, shown in Fig. 3-26, fixed-ratio coils, equal in value, are employed, and the bridge is balanced by adding a resistance r to the near leg of the faulty conductor.

$$\frac{a}{b} = \frac{r + x}{y + l} \quad \text{or} \quad \frac{a + b}{b} = \frac{x + y + l + r}{y + l} \quad \text{ohms}$$

If $a = b$,

$$x = y + l - r \quad \text{or} \quad x = \frac{1}{2(x + y + l - r)} \quad \text{ohms}$$

The total line resistance $x + y + l$ is conveniently determined by shifting the battery connection from P to Q and making a new balance, r' . The equation then becomes $x = \frac{1}{2}(r' - r)$. When a and b are slightly unequal, a second set of readings should be taken with a and b interchanged and the average values of r and r' substituted in the foregoing equations.

3. *Opens*, such as O in Fig. 3-24, are located by measuring the electrostatic capacitance to ground (or to a good conductor) of the faulty conductor and of an identical good conductor; the position of the fault is determined from the ratio of the capacitances.
4. *Shorts and grounds* may be detected by sending through the defective conductor an alternating current of audible frequency, say 1000 Hz. A pickup coil connected to a telephone receiver worn on the head of the tester is then carried along the line; the note in the receiver will cease when the fault has been passed.

3.1.14 Inductance Measurements

The *self-inductance*, or *coefficient of self-induction*, of a circuit is the constant by which the time rate of change of the current in the circuit must be multiplied to give the self-induced counter emf. Similarly, the *mutual inductance* between two circuits is the constant by which the time rate of change of current in either circuit must be multiplied to give the emf thereby induced in the other circuit. Self-inductance and mutual inductance depend upon the shape and dimensions of the circuits, the number of turns, and the nature of the surrounding medium.

Computable standards of self- or mutual inductance have been used traditionally in *absolute-ohm* determinations, but they are not suitable for use in assigning the values of other inductors—they are bulky and have relatively large capacitance to ground and considerable coupling to other circuits, their ratio of inductance to resistance is relatively low, and they exhibit appreciable skin effect even at moderately high frequencies, since they must be wound with rather heavy wire. All these undesirable features inevitably follow from the requirement that their values be computable from measured dimensions. Computable self-inductors and the primaries of computable mutual inductors are wound as single-layer solenoids on a dimensionally stable nonmagnetic form. The best of them are on cylinders of fused silica, and the winding is laid in a groove lapped into the form to ensure uniform winding pitch. The primary winding of a computable mutual inductor is in two or three sections spaced at such intervals that there is a region outside and in its central plane in which its field gradients are very small. The secondary—a multilayer winding—is located in this position so that its position and dimensions will be less critical.

Working standards of inductance are usually multilayer coils wound on nonmagnetic forms of Bakelite, marble, or ceramic to ensure reasonable dimensional stability. A toroidal core gives a coil that is practically immune to external magnetic fields. Approximate astaticism is also achieved by using two equal coils, connected in series and so located with respect to each other that their coupling with external fields tends to cancel each other. Since there is always capacitance associated with a winding, the effective value of an inductor will always be a function of frequency to a greater or lesser extent, and an accurate statement of value must necessarily include the frequency with which the value is associated. Inductance standards for radio frequencies are wound on open frames.

Single-layer winding or “loose basket weave” is essential to reduce the distributed capacitance and the consequent change of effective inductance with frequency. Insulating material is kept to a minimum to reduce dielectric loss.

Inductometers are continuously adjustable inductance standards. The Ayrton-Perry inductometer uses pairs of coaxial coils wound on zones of spheres; the outer pair is fixed, and the inner pair can be rotated about a vertical axis. The coils are so proportional that the scale is uniform over most of its length. This inductometer is not astatic, and its coupling with external fields can cause significant measurement errors. The Brooks inductometer, a better design from several viewpoints, consists of six link-shaped coils. The four stator coils are mounted in pairs above and below the rotor coils, which are located diametrically opposite one another in a flat disk. These two fixed- and moving-coil combinations are so connected that their coupling with external fields tends to cancel. The shape of the link coils gives a scale that is completely uniform except at its extreme ends, and the time constant of the inductometer is much higher than in the Ayrton-Perry arrangement. Ratio of maximum to minimum inductance is about 8:1, and change of calibration with wear in the bearings is negligibly small. Terminals of the fixed and movable coils are usually brought out separately so that inductometers can be used as either adjustable self-inductors or adjustable mutual inductors.

Measurement methods at power and audio frequency are (1) null methods employing bridges if accurate values are required or (2) deflection methods in which the inductance is computed from measured values of impedance and power factor, the measurements being made with indicating instruments—ammeter, voltmeter, wattmeter. At radio frequencies, resonance methods are used.

Bridges for inductance measurements can assume a variety of forms, depending on available components and reference standards, magnitude and time constant of the inductance to be measured, and a variety of other factors. In a four-arm bridge similar to the Wheatstone network, an inductance can be (1) compared with another inductance in an adjacent arm with two resistors forming the “ratio” arms or (2) measured in terms of a combination of resistance and capacitance in the opposite arm with two resistors as the “product” arms. It is generally better, where possible, to measure inductance in terms of capacitance and resistance rather than by comparison with another inductance because the problems of stray fields and coupling between bridge components are more easily avoided. The basic circuits will be described for a few bridges which can be used to measure inductance, but a more detailed reference should be consulted for a discussion of shielding, physical arrangement of components, effects of residuals, etc. In the balance equations which will be stated below, the inductance, L or M , will be expressed in henrys, the resistance R in ohms, capacitance in farads, and ω is $2\pi \times$ frequency in hertz. The time constant of an inductor is L/R ; its storage factor Q is $\omega L/R$.

Inductance comparison is accomplished in the simple Wheatstone network shown in Fig. 3-27, in which A and B are resistive ratio arms, L_x and r_x represent the inductor and the associated resistance being measured, and L_s and r_s are the reference inductor and the associated resistance (including that of the inductor itself) required to make the time constants of the two inductive arms equal. At balance,

$$\frac{A}{B} = \frac{L_x}{L_s} = \frac{r_x}{r_s}$$

An inductometer may be used to achieve balance, together with an adjustable resistance in the same bridge arm, as indicated in the diagram. If only a fixed-value standard inductor is available, balance can be secured by varying one of the ratio arms, but there also must be an adjustable resistance in series with L_x or L_s to balance the time constants of the inductive arms. Care must be taken to ensure that there is no inductive coupling between L_s and L_x , since this would lead to a measurement error.

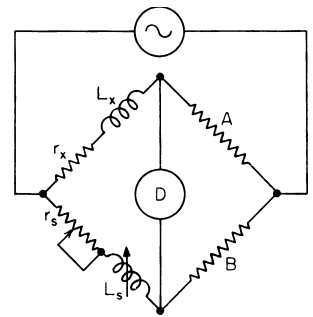


FIGURE 3-27 Inductance bridge.

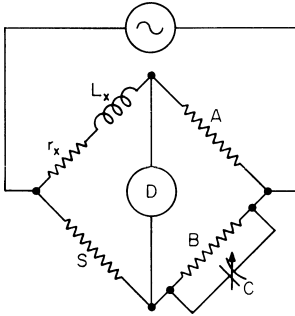


FIGURE 3-28 Maxwell-Wien inductance-capacitance bridge.

The *Maxwell-Wien bridge* for the determination of inductance in terms of capacitance and resistance is shown in Fig. 3-28. The balance equations are $L_x = ASC$ and $r_x = AS/B$. This bridge is widely used for accurate inductance measurements. It is most easily balanced by adjustments of capacitor C and resistor B ; these elements are in quadrature, and therefore their adjustments do not interact.

Anderson's bridge, shown in Fig. 3-29, can be used for measurement over a wide range of inductances with reasonable values of R and C . Its balance equations are $L_x = CAS(1 + R/S + R/B)$ and $r_x = AS/B$. Balance adjustments are best made with R and r_x . This bridge also has been used to measure the residuals of resistors, a substitution method being employed in which the unknown and a loop of resistance wire with calculable residuals are substituted in turn into the L arm. If A and B are equal and if the resistances of the unknown and the calculable loop are matched, the residuals in the various bridge arms do not enter the final calculation, except the

residual of Δr_x , the change in r_x between balances. The elimination of bridge-arm residuals from the *exact* balance equations is characteristic of substitution methods, and quite generally, residuals or corrections to the arms that are unchanged between the balances do not have to be taken into account in the final calculation when the difference is small between the substituted quantities.

Owen's bridge, shown in Fig. 3-30, can be used to measure a wide range of inductance with a standard capacitor C_b of fixed value, by varying the resistance arms S and A . In operation, the resistance S and capacitor $C_b(r_b)$ are usually fixed, balance being secured by successive adjustments of A and R . At balance,

$$r_x + R = (C_b/C_a)S + \omega L_x \omega C_b r_b$$

and $L_x(1 + \tan \delta_b \tan \delta_x) = C_b S(A + r_a)$. If $C_b(r_b)$ is a loss-free air capacitor so that $r_b = 0$ and $\tan \delta_b = 0$, $r_x = (C_b/C_a)S' - R$ and $L_x = C_b S(A + r_a)$. This is a bridge which is much used for examining the properties of magnetic materials; inductance may be measured with direct current superposed. With a low-reactance blocking capacitor in series with the detector and another in series with the source, a dc supply may be connected across the test inductance without current resulting in any other branch of the network; a high-reactance, low-resistance "choke" coil should be connected in series with the dc source.

Mutual inductance can be measured readily if an adjustable standard of proper range is available. Connections are made so the range of measurement is limited to values that can be read with the desired precision. Care should be taken in arranging the circuit to avoid coupling between the mutual inductors.

Iron-cored inductors vary in value with frequency and current, so measurements must be made at known current and frequency; bridge methods can, of course, be adapted to this measurement, care being exercised to ensure that the current capacities of the various bridge components are not exceeded. In such a case, the waveform of the voltage drop across the circuit branch containing the inductor may not be sinusoidal, whereas that across the other side of the bridge, containing linear resistances and reactances, may be undistorted. Generally, a tuned detector should be used.

Resonance methods can be used to measure inductance at radio frequencies. A suitable source is used to establish an rf field whose wavelength is λ m. The inductance L_x (microhenrys) to be measured is placed in this field and connected to a calibrated variable capacitor through a thermocouple

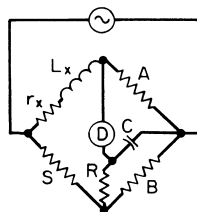


FIGURE 3-29 Anderson's bridge.

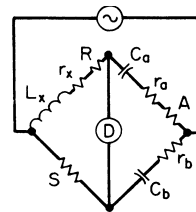


FIGURE 3-30 Owen's inductance-capacitance bridge.

ammeter (i.e., a current-indicating instrument without reactance). The capacitor is adjusted to resonance at a value of C (picofarads). Then, $L_x = 0.2815\lambda^2/C$. If a calibrated inductor L_s of the same order as L_x is available, the wavelength need not be known, and a substitution method can be used. The resonance settings are C_s and C_x , with L_s and L_x , respectively, in the circuit. Then, $L_x = L_s C_s / C_x$. The value of L_x is the effective inductance at the frequency of measurement and includes the effect of associated coil capacitance. The frequency of the source must not be affected by the substitution of L_x for L_s .

A *resonance-impedance method*, suitable for high frequencies, is indicated in Fig. 3-31. The capacitor C is adjusted until the same current is indicated by the ammeter with switch K open or closed. (The applied voltage must be constant.) Then, $L_x = (1/2\omega^2 C)$ H if C is in farads and the frequency is $f = \omega/2\pi$. The waveform must be practically sinusoidal and the ammeter of negligible impedance. This method may be used to measure the effective inductance of choke coils with superposed direct current.

The *residual inductance* of a resistor or a length of cable at high frequency often can be determined by connecting the resistor in series with a fixed air capacitor and measuring its effective capacitance in an appropriate bridge with and without the series resistor S . If C_1 and C_2 are the measured capacitances in farads, without and with the series resistor, then

$$L = \frac{C_2 - C_1}{\omega^2 C_1 C_2} \quad \text{and} \quad S = \frac{1 - \omega^2 L C_1}{\omega C_1} \tan \delta$$

S is the effective resistance in ohms. L is the residual inductance in henrys, and δ is the loss angle of the capacitor-resistor combination computed from the second bridge balance.

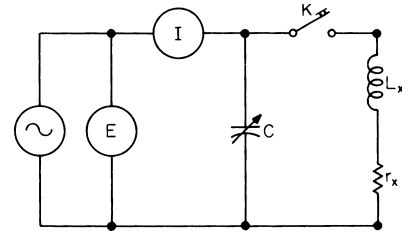


FIGURE 3-31 Reactance-impedance method of measuring inductance.

3.1.15 Capacitance Measurements

The *capacitance* between two electrodes may be defined for measurement purposes as the charge stored per unit potential difference between them. It depends on their area, spacing, and the character of the dielectric material or materials, which is affected by the electric field between them. The value of a capacitor, measured in farads or a convenient submultiple of this unit, will be influenced quite generally by temperature, pressure, or any ambient condition that changes the dimensions or spacing of the electrodes or the characteristics of the dielectric. The *dielectric constant* of a material is defined as the ratio of the capacitance of a pair of electrodes, with the material occupying all the space affected by the field between them, to the capacitance of the same electrode configuration in vacuum.

Computable capacitors known to 1 part in 10^6 or better have been constructed at the NIST and at certain other national laboratories as a basis for their *absolute-ohm* determinations. Such capacitors now serve as the “base” unit in assigning values to standard capacitors. The electrode arrangement of these computable capacitors conforms to the geometry prescribed in the *Thompson-Lampard theorem*: If four cylindrical conductors of arbitrary sections are assembled with their generators parallel to form a completely enclosed cylinder in such a way that the internal cross capacitances per unit length are equal, then in vacuum these cross-capacitances are each

$$\frac{\ln 2}{4\pi^2\mu_0 V^2}$$

In the mksa system of electrical units, where μ_0 has the assigned value $4\pi \times 10^{-7}$ and V is the speed of light in vacuum in meters per second, this capacitance is in farads per meter. The capacitance of such a cross capacitor is about 2 pF/m. A practical realization of such a capacitor consists of four equal closely spaced cylindrical rods with their axes parallel and at the corners of a square. Arranged as a three-terminal capacitor and with end effect eliminated, its value can be computed as accurately as its effective length can be measured.

The capacitance of vacuum capacitors with electrodes of simple geometry can be computed approximately in a few cases: (1) Flat, parallel plates with guard ring, $C = 0.08854A/t$ pF, where A is area of the guarded plate in square centimeters and t is spacing in centimeters between electrodes; if dimensions are in inch units, $C = 0.2249A/t$. (2) Coaxial cylinders with guard cylinders at both ends, $C = 0.24161L/\log(R_2/R_1)$ pF for centimeter units, or $C = 0.6137L/\log(R_2/R_1)$ pF for inch units, where L is the length of the guarded cylinder, R_1 is the radius of the inner cylinder, and R_2 the radius of the outer cylinder. (3) Concentric spheres, where R_1 is the radius of the inner sphere and R_2 is the radius of the outer sphere, $C = 1.1127R_1R_2/(R_2 - R_1)$ pF for centimeter units, or $C = 2.8262R_1R_2/(R_2 - R_1)$ pF for inch units. These formulas give only approximate values because they assume no contributing field beyond the edges of the bounding surfaces and take no account of possible eccentricity, lack of parallelism of surfaces, finite width of gap between guard and working electrode, etc., all of which would require small correction terms.

Standard capacitors at levels up to 10^3 pF are generally of a multiple-parallel-plate variety with dry gas (air or nitrogen) as dielectric. Low-temperature coefficient is secured by use of Invar—a low-expansion alloy—as the electrode material and a good degree of stability is achieved by careful, strain-free mounting of fully annealed components and by hermetically sealing the unit. A very high degree of stability has been achieved in a solid-dielectric construction at the 10-pF level in which a disk of fused silica is provided with fired-on silver electrodes. Direct capacitance is through the interior of the disk between its parallel faces, and a silver coating on the cylindrical face acts as guard electrode and confines the field. Very narrow gaps at the edges of the disk between the guard and active electrodes, together with continuation of the shielding in the mounting arrangement, eliminate the possibility of any portion of the measured capacitance being through an outside path between the parallel-plate electrodes. The assembly is hermetically sealed in dry nitrogen, in a shock-resistant, resilient mounting together with a resistance thermometer so that temperature corrections can be accurately applied. Standards of this type have shown variations less than 1 part in 10^7 over a year interval. From 10^3 pF to 1 μ F, standard capacitors generally have clear mica as dielectric. The electrodes may be metal foils laid out between the mica sheets, the assembly impregnated with paraffin, and the excess wax squeezed out under high pressure. In an alternative construction, the mica sheets are silvered, assembled under pressure, and the assembly hermetically sealed. Neither construction is as stable with time as the lower-value air-dielectric units, and the mica units are characterized by low but appreciable loss angles, whereas the loss angle of the air-dielectric standards is negligible in almost all applications. Continuously adjustable air capacitors have two stacks of interleaved parallel metal plates, one stack being mounted to rotate on an axis. The maximum capacitance occurs when the fixed and movable plates completely overlap; the minimum, a small value but not zero, occurs 180° from this position.

A *three-terminal construction* is required if the value of the capacitor is to be definite and independent of its proximity to other objects. In a nominally two-terminal arrangement, each of the electrodes has some capacitance to surrounding objects or to ground which may depend on spacing and which actually forms a second capacitance circuit in parallel with the capacitor of interest, as will be seen from Fig. 3-32a and b. It is only in case c, where there is an actual third electrode which completely encloses the other two, that the value can be made definite and completely independent of any object or field outside the assembly. A second advantage of the three-terminal construction is that the direct capacitance between the two enclosed electrodes can be made loss-free, since the solid insulation required to support them mechanically can be in the auxiliary capacitances between the enclosing shield electrode and the shielded electrodes.

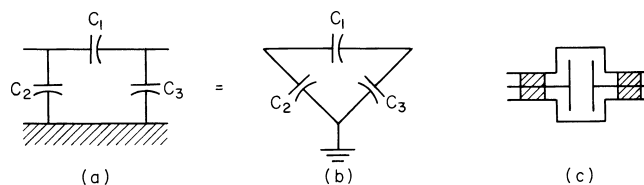


FIGURE 3-32 Two-terminal and three-terminal capacitors.

Methods of measuring capacitance can be classified as *null* methods, which quite generally involve the use of bridges, and *deflection* methods, in which some characteristic, usually impedance, is measured with the aid of indicating instruments. In the equations that follow, the capacitance C will be expressed in farads and resistance A, B, S in ohms. δ will be the *loss angle*, the amount which the current lags of a true quadrature relation with voltage. The *power factor* of a capacitor is then $\cos(\pi/2 - \delta) = \sin \delta$. The dissipation factor D is the name given to $\tan \delta$. It is convenient to represent a capacitor as consisting of a capacitance C (farads) in series with a resistance r (ohms) such that $\tan \delta = 2\pi fCr$ at a frequency f . The *power loss*, for an impressed voltage E (volts), is $P = 2\pi fCE^2 \sin \delta$. Since most bridges yield $\tan \delta$, the power loss can be expressed conveniently as $P = 2\pi fCE^2 \tan \delta$, where δ is small, or $P = \omega CE^2 D$.

Bridge methods for the comparison of capacitors are to be preferred over methods in which capacitance is determined in terms of inductance, since it is simple to shield capacitors so that their values are completely independent of neighboring objects and their electric fields are completely confined, whereas the magnetic fields of inductors cannot be so confined. Error voltages can enter bridges through coupling of an inductor with an external field, through mutual coupling with eddy-current circuits induced by the inductor in neighboring metal objects, etc.

DeSauty's bridge, shown in Fig. 3-33, is a simple Wheatstone network in which capacitors may be compared in terms of a resistance ratio. It should be noted that the loss angles of the two capacitance arms must be equal, so a series resistor is inserted in the branch with the smaller loss angle. In the case illustrated, the resistance S is in series with the reference capacitor C_s . At balance, $C_x = C_s(B/A)$, and $\tan \delta_x = \omega C_x r_x = \omega C_s(r_s + S) = \tan \delta_s + \omega C_s S$.

Schering's bridge, shown in Fig. 3-34, has found wide application in measuring the loss angles of high-voltage power cables and high-voltage insulators. For this purpose, the supply voltage is connected as shown, and a ground connection is made at the junction of branches A and B so that the balance adjustments may be made close to ground potential. The adjustable components are generally A and C_p . It is also customary to enclose the A, B , and detector branches in a grounded screen and to protect this low-voltage section against possible breakdown of the test specimen by an air gap paralleling branch A . Such a gap can be set to spark over at 100 V or so, and provides a low-resistance path to ground for breakdown current from the specimen. The balance equations are $C_x = C_s(B/A)(1 + \tan \delta_s \tan \delta_p)$ and $\tan \delta_x = \omega C_p B + \tan \delta_s$. Usually, the reference capacitor C_s is a high-voltage air or compressed-gas capacitor with a negligible phase-defect angle, in which case the correction terms to the balancing equation drop out. The Schering bridge is also an excellent one to use for the comparison of capacitors at low voltage. For this purpose, it is used in its conjugate form with supply and detector branches interchanged to increase sensitivity. C_p must, of course, be connected across branch A instead of B if the loss angle of C_s is greater than that of C_x , with a corresponding modification of the balance equations. When the loss angles of C_s and C_x are both very small, adjustable capacitors must be connected across both A and B arms, and the difference in the phase-defect angles they introduce into the bridge must equal the difference in loss angles of C_s and C_x . This modification of the bridge is made necessary by the fact that the capacitance of an adjustable capacitor cannot be reduced to zero in the usual construction.

The *transformer bridge* has been developed into the most precise tool available for the comparison of capacitors, especially for three-terminal capacitors with complete shielding. A three-winding transformer is used so that the bridge ratio is the ratio of the two secondary windings of the transformer which are of low resistance and uniformly distributed around a toroidal core to minimize leakage reactance. A stable ratio, known to better than 1 part in 10^7 , can be achieved in this way.

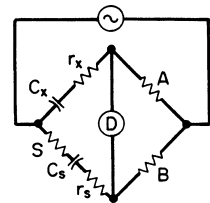


FIGURE 3-33 DeSauty's bridge.

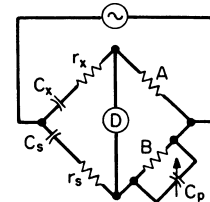


FIGURE 3-34 Schering's bridge.

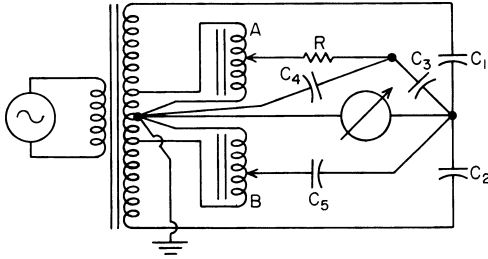


FIGURE 3-35 Transformer bridge for capacitor comparison.

A number of schemes for balancing adjustment have been used successfully. One of these, employing *inductive voltage dividers*, is shown schematically in Fig. 3-35 but simplified by omitting the necessary shielding. Current in phase with the main current is injected at the junction between the capacitors being compared, C_1 and C_2 , to balance their inequality in magnitude. This current, through capacitor C_5 , is controlled by adjusting the tap position on inductive voltage divider B , supplied from an appropriate tap point on the main transformer-ratio arm. Quadrature current, to

balance the phase difference between C_1 and C_2 , is similarly injected through R and the current divider $C_3/(C_3 + C_4)$, controlled by adjusting the tap point on divider A . The current divider is used so that R may have a reasonable value, a few megohms at most. In the illustrated network, it is assumed that $C_1 > C_2$ and that $\delta_1 < \delta_2$. The balance equations are $C_2 = C_1 + N_B C_5$ and $\delta_2 = \delta_1 + \omega R C_1 \cdot N_A \cdot C_3/(C_3 + C_4)$, where N_B is the fraction of the voltage across C_2 which is impressed on C_5 , that is, the product of the tap-point ratios of the main transformer and divider B , and N_A is the corresponding fraction of the voltage across C_1 which is impressed on R . The reactance of C_3 and C_4 in parallel must be small compared with the resistance of R .

New automated impedance measurement instruments have come into being because of the ready availability of microprocessors. Some of these make use of the transformer techniques mentioned earlier, using relays to balance them by selecting ratios computed by the microprocessor from detector output voltages. Many have purely analog quadrature balance features. At least, one measures by passing the same current through the admittance to be measured and a reference resistor and computing the vector impedance of the unknown from the vector ratio of the voltage drops across it and the reference resistor. This is done using a 90° phase reference generated internally using digital synthesis techniques.

Many automated bridges are intended for testing of precision components over a broad range of frequencies and with programmable direct current or voltage biases. Their accuracies range from a few percent at high frequencies to 0.01% or better at audio frequencies. Their calibration is generally done using fixed-value two- or three-terminal or four-pair-terminal standards.

Detectors used in bridge measurements are selected with regard to frequency and impedance. *Vibration galvanometers* can be used at power frequencies in low-impedance circuits; they discriminate well against harmonics and have high sensitivity, but they must be tuned sharply to the use frequency.

Wave analyzers, which are commercially available with internal crystal control, also have a narrow passband and a high rejection of frequencies on either side. They can be used with a preamplifier when maximum sensitivity is required, and it is desirable that the preamplifier itself be sharply tuned in its first stage to improve noise rejection. This system can be used at any frequency throughout the audio region.

Cathode-ray oscilloscopes of adequate sensitivity (or used with tuned preamplifiers) make particularly good null detectors. If a phase-adjustable voltage from the bridge supply is impressed on the horizontal plates and the unbalance signal in the detector branch impressed on the vertical plates, the resulting Lissajous figure is an ellipse which, with proper phase adjustment, will change its opening with magnitude adjustment and the slope of its major axis with quadrature adjustment in the bridge. Balance is indicated by a straight horizontal trace on the screen. It is essential in this system that the initial stages of amplification be sharply tuned or that the bridge input be sinusoidal, for otherwise the pattern on the screen is confused and difficult to interpret. Phase discrimination of this type in the null detector is of considerable value in achieving balance, since it informs the operator of the individual magnitudes of inphase and quadrature unbalance.

Telephone receivers may be used at audio frequencies (maximum sensitivity being at about 1 kHz), but their response is usually quite broad, and the balance point may be masked by the presence of harmonics.

In *resonance methods* at radio frequencies, a thermocouple ammeter can be employed to show the current maximum. A crystal rectifier with an electronic voltmeter is used at ultrahigh frequencies.

Precautions in Bridge Measurements. The effect of stray magnetic fields can be minimized by using twisted-pair or coaxial leads and by avoiding loops in which an emf could be induced. Inductive coupling between bridge components should be avoided. Capacitive coupling existing between parts of the bridge which are not at the same potential will impress shunt capacitance across one or more of the bridge arms and modify the balance condition. Shielding must be used to minimize these effects.

Resonance methods are used for capacitance measurements at radio frequencies, a coil of known inductance L (microhenrys) at a known wavelength λ (m) being employed. Resonance is produced by varying λ and is detected with a thermocouple ammeter. At resonance, $C_x = 0.2815\lambda^2/L$ in picofarads. λ and L need not be known if a substitution method is used in which an adjustable capacitor with a range that includes C_x is connected in place of the unknown capacitor and adjusted to resonance without altering the frequency so that $C_x = C_s$. The leads used to connect the capacitors into the circuit must not be changed in length or position in making the substitution.

A *cavity resonator* can be used at frequencies on the order of 200 to 1000 MHz for measuring the characteristic of insulating material placed between electrodes within the cavity. Resonance is established with excitation of a small loop of wire within the cavity by connection to an oscillator, and resonance is shown by a crystal-rectifier probe connected to an electronic voltmeter.

3.1.16 Inductive Dividers

Inductive dividers are employed in precise voltage- and current-ratio applications. The ratios are used for comparing impedances and for calibrating devices with known nominal ratios such as other dividers, synchros, and resolvers. A divider usually consists of an autotransformer adjustable in decade steps. Such transformers, with high ratio accuracy for voltage or current comparison, have been made by using high-permeability magnetic-core materials and ingenious winding and connection techniques. Such a transformer can be represented electrically by the equivalent circuit of Fig. 3-36. The components of this circuit can be measured directly and will predict the performance of the divider. D is a perfect divider with infinite input impedance and zero output impedance. A' is the transfer ratio of D , the ratio of the voltage between the open-circuited *tap point* and the *low* end to the voltage between the *high* and *low* ends. A' is also the ratio of the short-circuit current between the high and low ends to the current into the tap point and out of the low point. Z_{oc} is impedance between high and low points, with the tap point open-circuited. This impedance is quite high and is a function of input voltage and frequency primarily. Its major components are the winding capacitance, charging inductance, and leakage reactance in parallel. Z_{sc} is the impedance between tap and low points, with the high and low points short-circuited together. This impedance is quite low and is a function of frequency and setting. Its major components are winding and contact resistances and the leakage inductance in series. The autotransformer configuration can produce voltage and current ratios of very high accuracy.

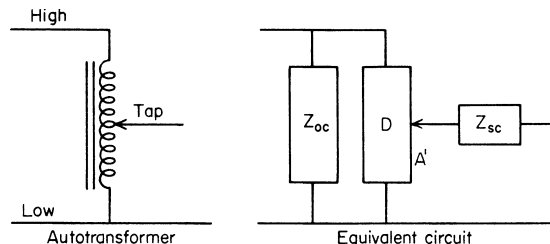


FIGURE 3-36 Autotransformer and equivalent circuit.

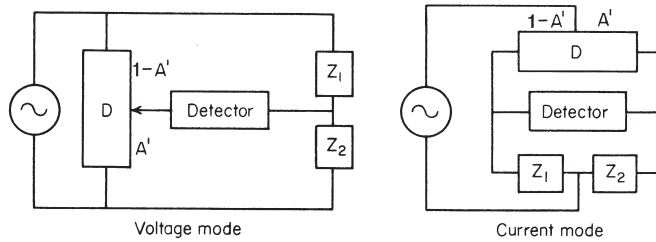


FIGURE 3-37 Voltage mode (left) and current mode (right) for impedance comparison

As a *voltage divider*, the circuit can be represented by a Thévenin equivalent consisting of a zero-impedance generator, with a voltage which is the product of the input voltage times the transfer ratio, and an output impedance equal to Z_{sc} . This low-output impedance provides high accuracy even with appreciable load admittance. For example, a $5000\text{-}\Omega$ load will change the output voltage by only 0.1% if the output impedance is $5\text{ }\Omega$.

As a *current divider*, the circuit can be represented by Norton equivalent consisting of an infinite-impedance generator, with a current which is the product of the transfer ratio A' and the input current and an impedance equal to Z_{oc} in shunt across the output. This high-shunt output impedance provides high accuracy even with appreciable load impedance. For example, a $500\text{-}\Omega$ load will receive a current only 0.1% less than short-circuit current if the output impedance Z_{oc} is $500,000\text{ }\Omega$.

Impedance comparison, using the comparison ratio $A'/(1 - A')$, can be accomplished in either the voltage mode of operation or the current mode of operation, as shown in Fig. 3-37. For impedance comparison, the divider impedances Z_{oc} and Z_{sc} are of no consequence. In the voltage-ratio mode, Z_{oc} is outside the bridge circuit, and at null no current is drawn through Z_{sc} . In the current-ratio mode, Z_{sc} is outside the bridge circuit, and at null there is no voltage across Z_{oc} . In either mode, the balance equation is $Z_2 = Z_1 A'/(1 - A')$.

3.1.17 Waveform Measurements

The instantaneous variations of current and voltage in a circuit can be measured by oscillographs, whose basic operating principle may be either that of a D'Arsonval galvanometer whose inertia is low enough to permit it to follow the variations or that of an electron beam which has no sensible inertia and whose deflection is governed by electric or magnetic fields. In addition to tracing waveforms, oscillographs are used for measurements of transient phenomena, such as those which occur in switching operations or in the impulse-voltage testing of insulating structures and disturbances resulting from lightning discharges. Transient phenomena also may be captured using digitizing oscilloscopes and transient digitizers (waveform recorders).

The *galvanometer oscillograph* may have a light low-inertia coil or, for higher-frequency response, a pair of thin metal ribbons tightly stretched across insulating bridges and tied together by a small mirror at their midpoints, mounted in the field of a permanent magnet. A light beam from the galvanometer mirror traces its response to varying current on a moving photographic film or, by means of an intermediate rotating mirror, on a stationary viewing screen. Galvanometer elements have been built with natural response frequencies as high as 8 kHz (a more common construction has a resonance frequency of about 3 kHz) and, if damped at about 0.7 of critical, have a response to signals which is practically free from distortion up to about half their resonant frequency; at resonant frequency, the deflection sensitivity has decreased to about 70% of their dc sensitivity for this damping.

3.1.18 Frequency Measurements

Reed-type frequency meters have a number of steel strips rigidly fastened to a bar at one end and free to vibrate at the other. These strips are located in the field of an electromagnet which is energized

from the circuit whose frequency is to be measured. The strips have been accurately adjusted by solder weights to resonant vibration frequencies that differ by $\frac{1}{4}$ or $\frac{1}{2}$ Hz, and the one with a period corresponding to the alternations of the voltage will be set into vibration. The free ends of the strips or reeds are turned up and painted white so that the reed which is vibrating will be indicated by an extended white band or blur.

The *Weston frequency meter* has fixed coils, 90° apart, and a movable element consisting of a simple, soft-iron core mounted on a shaft, with no control of any kind.

Resonant circuit meters, operating from circuits containing inductance and capacitance, can be made sensitive enough to indicate frequency variations of 0.01 Hz or less.

Precise frequency control is also accomplished with resonance techniques. Small-range indicators or recorders can be built as relays to monitor the frequency of a power system or generator, injecting an appropriate signal into a control system to restore frequency to a particular value. Such control may be made precise enough for use of the system frequency for electric-shock operation. Any tendency to frequency drift may be detected and corrected at the source by comparing an electric clock with a precise pendulum clock or one driven by a quartz-crystal oscillator.

Radio frequencies may be measured directly or indirectly. Direct measurement may be made with a wavemeter, an instrument with a tunable circuit and an ammeter to indicate the resonance frequency by a current maximum. In the indirect method, the unknown-frequency signal is introduced into a circuit with a precisely known frequency, and the beat frequency is counted. Quartz crystals maintained in temperature-regulated ovens will control the frequency of an oscillator to much better than 1 part in 10^6 . Such a crystal-controlled oscillator, serving as a local reference standard of frequency, can be monitored against the very precise *standard* frequencies continuously broadcast by the NIST from its low-frequency station WWVL, operated at 60 kHz, or its high-frequency stations WWV and WWVH, which broadcast at a large number of higher frequencies. These broadcast frequencies are controlled by crystals operating under conditions that are most favorable to stability and are, in turn, monitored against the frequency of an atomic-beam resonator. The transmitted frequencies, as sent from the bureau stations, are accurate to about 1 part in 10^{12} . Frequencies from these broadcasts are modified somewhat in transmission by diurnal and moment-to-moment variations in the ionosphere, and their accuracy as received may be reduced by more than an order of magnitude.

Audio frequencies can be measured with a frequency-sensitive bridge, such as the Wien bridge with parallel- and series-connected capacitance-resistance arms, or they can be conveniently observed with a cathode-ray oscilloscope, if a known reference frequency is available. One set of plates of the oscilloscope is excited by the known- and the other set by the unknown-frequency signals. If the two frequencies have an exact, simple fractional relation, the Lissajous figure formed on the screen is stationary. For a 1/1 relationship, the pattern is an ellipse; for other fractional relationships, the pattern is more complicated, the relationship being determined from the number of loops. If the relationship cannot be represented by a simple fraction, the pattern will change continuously, and a count of the beat frequency is made over a measured time interval.

Electronic counters are widely used for frequency measurements. They work by counting the number of cycles of an input signal, or events, which occur in a very accurately known time interval (gate time). The gate time is based on the output of an internal standard oscillator (clock) or, optionally, on a reference-frequency signal input to the counter. Most counters of laboratory quality also can be used to measure the period of low-frequency signals, time intervals, the ratio of the frequencies of two input signals, and a total number of events. They also afford control of triggering, thus enabling the user to set trigger levels and slopes, noise rejection levels, and input attenuation levels. Output is via digital display, ranging from six to nine digits, and (usually) high-speed digital computer interface. Accuracies of frequency measurements are usually stated by the manufacturer to be $\pm$ clock accuracy $\pm$ 1 count. Most laboratory-grade counters can be equipped with high-stability crystal-based clocks, mounted in temperature-controlled ovens, and are stated to have drift rates as low as 2×10^{-8} per month. The frequency ranges covered are from nearly dc, directly or via period measurements, to as high as 500 MHz directly and to over 30 GHz using heterodyning techniques.

3.1.19 Slip Measurements

The *slip* of a rotating ac machine is the difference between its speed and the synchronous speed, divided by the synchronous speed; slip is usually expressed as a percentage. It may be computed from the measured speed of the machine and the synchronous speed, but direct methods are more accurate.

Millivoltmeter Method. If sufficient stray field is produced by the current in the secondary of an induction motor, a dc millivoltmeter connected to an adjacent coil of wire or across the motor shaft or frame will oscillate at slip frequency, each swing being one pole slip. In motors with wire-wound rotors, the millivoltmeter may be connected across the rotor slip rings.

Stroboscopic Method. In Fig. 3-38, a black disk with white sectors, equal in number to the number of poles of the induction motor, is attached to the induction-motor shaft. It is observed through another disk having an equal number of sector-shaped slits and carried on the shaft of a small self-starting synchronous motor, in turn fitted with a revolution counter which can be thrown in and out of gear at will. If n is the number of passages of the sectors, then $100n/n_s n_r = \text{slip in percent}$, where n_s is the number of sectors and n_r is the number of revolutions recorded by the counter during the interval of observation. For large values of slip, the observations can be simplified by using only one sector ($n_s = 1$); then $n = \text{slip in revolutions}$.

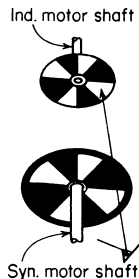


FIGURE 3-38 Slip measurement by stroboscopic method.

With a *synchronous light source* to illuminate the target on the induction-motor shaft, the synchronous motor is no longer necessary. An arc lamp connected across the ac supply may be used, but the carbons must be readjusted from time to time. A neon lamp makes a satisfactory source of light when the general illumination is not too bright. A portable stroboscope may

consist of a gaseous discharge tube backed by a parabolic reflector to concentrate the light beam and an adjustable-frequency voltage source to trigger the flashlamp synchronously. The flash also can be triggered externally. Light output measured 1 m from the lamp may exceed 10^6 candela and flash duration may be as low as $0.5 \mu\text{s}$.

Synchronizing. In order to connect any synchronous machine in parallel with another machine or system, the two voltages must be made equal and the machines must be synchronized, that is, the speed

so adjusted that corresponding instantaneous values on the two waves are reached at the same instant, when they will be in exact phase. Furthermore, with polyphase machines, the direction of phase rotation must assuredly be the same. This, however, is usually made right once and for all when the machines are installed, the phases being so connected to the switches that the phase rotation will always be correct.

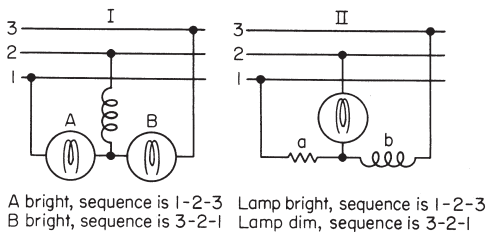


FIGURE 3-39 Phase-sequence indicators.

The *phase sequence of a 3-phase system* is often desired. Figure 3-39 shows two lamp methods. In I, two lamps and a highly reactive coil, such as the potential coil of a watt-hour meter, are used. The bright lamp indicates the

particular phase sequence. In arrangement II, a noninductive resistance and a reactive coil of equal impedance are used in conjunction with a lamp, the brightness of which indicates the sequence.

3.1.20 Magnetic Measurements

The two classes of magnetic measurements are *field measurements*, such as the earth's field or the field in the air gap of a magnet, and *measurements to determine the characteristics* of magnetic materials.

Magnetic field measurements are commonly made by induction methods in which a coil is placed with its plane perpendicular to the field. Removing the coil to a point of zero flux or reversing the coil will induce in it an emf that can be measured by the ballistic deflection of a galvanometer in terms of its flux-linkage sensitivity (when operating in a circuit having the resistance of the search-coil circuit). In this measurement, $\int e dt = N \Delta \phi 10^8$, where ϕ is the flux in maxwells enclosed by the coil and N is search-coil turns. The flux density B , in gauss, is ϕ/a , where a is the coil area in square centimeters.

The flux-linkage sensitivity of the galvanometer under the operating condition can be determined with the aid of a mutual inductor, with the galvanometer in the secondary circuit and a known current reversed in the inductor primary. Here, $\int e dt = 2MI$ volt-seconds, where M is mutual inductance in henrys and I is primary current in amperes. A Grassot-type fluxmeter can be used in place of a ballistic galvanometer. This is essentially a ballistic instrument in which restoring torque is reduced substantially to zero so that the deflection remains steady after the change in flux linkages.

Low field measurements are also made with magnetometers. This instrument uses a strip of high-permeability, low-coercive-force material (usually supermalloy) with an ac excitation coil that drives the material into saturation each half cycle at a frequency of a few kilohertz. A second-harmonic detector coil on the same strip will sense a bias field to which the assembly is exposed. A third coil on the strip supplies a measured offset ampere-turns to return the detector to zero, providing a very sensitive field measurement device. This is widely used in earth's field and other low-level field measurements. A portable flux-gate magnetometer, in which the vector-magnetic-field component at the sensor is neutralized by a current in a solenoid surrounding the sensor, has a resolution of 1 gamma at the neutralizing control. The magnitude (in gamma) of the neutralizing field is indicated on manually operated digital dials, and any difference between ambient field-vector component and neutralizing field is indicated on a meter whose range may be selected between 25 and 10^4 gammas. A nondirectional magnetometer system is based on proton gyromagnetic ratio and the functional relation between ambient field and resonance frequency in the sensor. This type of magnetometer is also used to sense small variations in the local earth's field.

Measurement of higher fields (20 to 20,000 G) and fields in spaces too confined for search coils are frequently made with Hall-effect gaussmeters. In a thin strip or film of a metal having a large Hall-effect coefficient and carrying a current, two points on opposite sides of the strip can be found between which there is no potential difference. If a magnetic field is then applied at a right angle to the plane of the strip, a potential will exist between these points which is proportional to the field. Germanium, bismuth, indium antimonide, and indium arsenide are the common materials for such probes, and they may be as small as 0.15×1.2 mm. Response of many of these instruments is fast enough to allow operation up to midrange audio frequencies.

In another type of gaussmeter, a small permanent magnet is suspended between taut bands. It will attempt to line up with any external field, and an attached pointer and scale can be calibrated in kilogausses. Such a device can be made to indicate both direction and magnitude of the external field to a somewhat limited accuracy.

DC magnetic materials testing is done either by providing a complete closed path of the sample material on which exciting and sensing windings can be placed or by utilizing a "yoke" type of apparatus to furnish excitation to a small sample with its own sensing winding. Closed-loop samples may be a toroid composed of a stack of punched rings, a toroid made by wrapping tape into a spiral, or a closed loop made by stacks of strip samples assembled with overlapped ends in an Epstein frame.

This arrangement, in the form of a square, has an excitation winding and a sensing winding distributed along the four sides of the square to enclose the sample. The geometry and construction of these coils is detailed in ASTM Standard A343, part 44 of the *Annual Book of ASTM Standards*. Punched-ring samples are not usually considered satisfactory for oriented materials, while either spiral-wrapped tape toroids or Epstein strip samples can be used in either oriented or nonoriented materials. In any of these closed-loop samples, the excitation can be determined in terms of the ampere-turns that supply it. If the mean diameter of the sample is large compared with its radial width, the excitation is calculated as $H = 0.4\pi NI/l$ oersteds, where N is the number of turns in the magnetizing winding, I is the current in amperes, and l is the mean path length of the ring in centimeters. In using Epstein samples, it is necessary to make an assumption as to the actual magnetic-path length. This is normally taken as 94 cm in

Magnetic susceptibility testing designates those measurements which require much more sensitive apparatus than the methods described above. Such tests are made by measuring the minute mechanical forces experienced when the sample is in a nonuniform field. All these systems—the Gouy, the Faraday, and the Thorpe-Senftle method—consist of a strong field in which the sample is placed and weighed. They differ in the method of obtaining a calculable nonuniform field.

Magnetic amplifier material testing is a specialized procedure for materials to be used in amplifiers. There are a number of special tests in use on a supplier-user agreement basis that have no universal

acceptance. ASTM Bulletin A598-69 specifies a number of recommended test points for various materials. These tests have the largest acceptance of any presently in use, and most suppliers are equipped to furnish material based on this type of testing. Test frequencies most commonly used are 60, 400, and 1600 Hz.

3.2 MECHANICAL POWER MEASUREMENTS

3.2.1 Torque Measurements

Torque is best measured with dynamometers, of which there are two classes: absorption and transmission. Absorption dynamometers absorb the total power delivered by the machine being tested, whereas transmission dynamometers absorb only that part represented by friction in the dynamometer itself. Made in a wide variety of forms, typical forms are described in the following paragraphs.

The Prony brake is the most common type of *absorption dynamometer*. The torque developed by the machine to overcome the friction is determined from the product of force required to prevent rotation of the brake and the lever arm. The load is applied by tightening the brake band or adding weights.

The *energy dissipated* in the brake appears in the form of heat. In small brakes, natural cooling is sufficient, but in large brakes, special provisions have to be made to dissipate the heat. Water cooling is the usual method, one common scheme employing a pulley with flanges at the edges of the rim which project inward. Water from a hose is played on the inside surface of the pulley and collected again by means of a suitable scooping arrangement. About 100 in² of rubbing surface of brake should be allowed with air cooling or about 25 to 50 in² with water cooling per horsepower.

The *Westinghouse turbine brake* employs the principle of the water turbine and is capable of absorbing several thousand horsepower at very high speeds.

In the *magnetic brake*, a metallic disk on the shaft of the machine being tested is rotated between the poles of magnets mounted on a yoke which is free to move. The pull due to the eddy currents induced in the disk is measured in the usual manner by counteracting the tendency of the yoke to revolve. This form of brake can be made in very small sizes and is therefore convenient for very small motors.

The principal forms of *transmission dynamometers* are the torsion and the cradle types. In *torsion dynamometers*, the deflection of a shaft or spiral spring, which mechanically connects the driving and driven machines, is used to measure the torque. The spring or shaft can be calibrated statically by noting the angular twist corresponding to a known weight at the end of a known lever arm perpendicular to the axis. When in use, the angle can be measured by various electrical and optical methods. The *cradle dynamometer* is a convenient and accurate device which is extensively used for routine measurements of the order of 100 hp or less. An electric generator is mounted on a "cradle" supported on trunnions and mechanically connected to the machine being tested. The pull exerted between the armature and field tends to rotate the field. This torque is counterbalanced and measured with weights moved along an arm in the usual manner.

3.2.2 Speed Measurements

Tachometers, or speed indicators, indicate the speed directly and thus include the time element. The principal types are centrifugal, liquid, reed, and electrical. In the *centrifugal type*, a revolving weight on the end of a lever moves under the action of centrifugal force in proportion to the speed, as in a flyball governor. This movement is indicated by a pointer which moves over a graduated scale. In the *portable or hand type*, the tachometer shaft is held in contact with the end of the shaft being measured, and in the *stationary type*, the instrument is either geared or belted. In the *liquid tachometer* of the Veeder type, a small centrifugal pump is driven by a belt consisting of a light cord or string.

This pump discharges a colored liquid into a vertical tube, the height of the column being a measure of the speed.

Reed tachometers are similar to reed-type frequency indicators, the reeds being set in resonant vibration corresponding to the speed of the machine. The instrument may be set on the bed frame of the machine, where any slight vibration due to the unbalancing of the reciprocating or evolving member will set the corresponding reed in vibration. Some forms are belted to the revolving shaft and the vibrations imparted by a mechanical device. *Electrical tachometers* may be either reed instruments operated electrically from small alternators geared or belted to the machine being measured or ordinary voltmeters connected to small permanent-magnet dc generators driven by the machine being tested.

Chronographs are speed-recording instruments in which a graphic record of speed is made. In the usual forms, the record paper is placed on the surface of a drum which is driven at a certain definite and exact speed by clockwork or weights, combined with a speed-control device so that 1 in on the paper represents a definite time. The pens which make the record are attached to the armature of electromagnets. With the pens in contact with the paper and making a straight line, an impulse of current causes the pen to make a slight lateral motion and, therefore, a sharp indication in the record. This impulse can be sent automatically by a suitable contact mechanism on the shaft of the machine or by a key operated by hand. The time per revolution is then determined directly from the distance between marks.

Stroboscopic methods are especially suitable for measuring the speed of small-power rotating machines where even the small power required to drive an ordinary speed counter or tachometer would change the speed, also for determining the speed of machine parts which are not readily accessible or where it is not practicable to use mechanical methods or where the speed is variable.

One convenient form of stroboscopic tachometer employs a neon lamp connected to an oscillating circuit supplied from a 60-Hz circuit, which is adjusted to "flash" the neon lamp at the frequency necessary to make the moving part that the lamp illuminates appear to stand still. Speeds from a few hundred to many thousands of revolutions per minute can be very conveniently measured.

3.3 TEMPERATURE MEASUREMENT

Temperature Scale. There is an international temperature scale, ITS-90 (International Temperature Scale of 1990), that came into effect on January 1, 1990 and superseded the IPTS-68 (International Practical Temperature Scale of 1968). All temperature measurements should be referred to the ITS-90. This scale extends upward from 0.65 K. The scale is defined in terms of ^3He and ^4He vapor pressure versus temperature relations, an interpolating constant-volume gas thermometer that is calibrated according to a specified procedure at designated fixed points to which temperature values have been assigned and that is used for interpolation according to specified equations, a set of defining fixed points to which temperature values have been assigned, and platinum resistance thermometers that are calibrated at specified sets of those fixed point and used for interpolation between those points according to designated reference and deviation functions, and Planck's radiation law referenced to any one of three fixed points to which temperature values have been assigned. Temperatures on the ITS-90 were in as close agreement with Kelvin thermodynamic temperatures as possible at the time the scale was adopted. The scale is maintained in the United States by the National Institute of Standards and Technology (NIST), and any laboratory may obtain calibrations from NIST based on this scale. In the region from 0.65 to 25 K, rhodium-iron resistance thermometers and/or germanium resistance thermometers are calibrated on the ITS-90 to an uncertainty of ± 0.001 K or less; in the range from 13.8 to 934 K, standard platinum resistance thermometers (SPRTs) are calibrated to an uncertainty of ± 0.001 K or less; in the range from 273 to 1235 K, high-temperature SPRTs (HTSPRTs) are calibrated to an uncertainty of ± 0.002 K. Above 1235 K, the ITS-90 is realized by means of Planck's radiation law, usually by calibrating a radiation thermometer, or pyrometer, at the freezing-point temperature of silver (1235 K), gold (1337 K), or copper (1358 K) and extrapolating to higher temperatures. The accuracy of the ITS-90 and the procedures used to calibrate the thermometers just described may be

found in the references in the Bibliography. The remainder of this section on thermometry will be devoted to thermometry at a less accurate but more practical level.

Thermoelectric Thermometers (Thermocouples). By far the most commonly used thermometer in practical situations is the thermocouple. It consists of a pair of dissimilar electrical conductors (usually wires) joined at two junctions. One junction is maintained at a reference temperature t_0 (usually the melting point of ice), while the other is maintained at the unknown temperature t . The temperature difference produces a thermal emf which is measured by a potentiometer or a precise digital voltmeter. The latter is especially appealing because it is automatic (i.e., self-balancing), of sufficient resolution, and may easily be interfaced to an automatic data acquisition system.

Metals Used for Thermocouples. There are eight combinations of metal and alloys most extensively used, and they are designated as type B, E, J, K, N, R, S and T. Table 3-2 gives their nominal composition, temperature range, and highest suitable temperature for short-term use without significant degradation in performance.

Types R and S may be used for temperatures up to 1480°C and type B to 1700°C. It is recommended that the wire diameters exceed 0.5 mm if the thermocouple is to be used for long times at the upper temperature. These thermocouples are recommended for use in air because they are made from noble metals which are resistant to oxidation. They are easily degraded by other conditions, however, so they should be enclosed in a protective sheath. Type J may be used in a vacuum, inert, oxidizing, or reducing atmosphere. Again, a large-diameter wire (at least 3 mm) is necessary for use at long times in an oxidizing atmosphere. Types K and N are used up to 1200°C in inert or oxidizing atmospheres. Type E thermocouples are especially suitable for cryogenic use and may be used in vacuums, inert, oxidizing, or reducing atmospheres. Type T thermocouples may be used in the same atmospheres as type E, but they should not be used above 370°C under oxidizing conditions.

Temperature-EMF Relations for Various Thermocouples. Standard emf versus temperature tables, based on the ITS-90, have been developed and are published for the standardized thermocouples in NIST Monograph 175. Most manufacturers produce wires of sufficient quality so that a thermocouple may be fabricated from the materials given in Table 3-2, and their emf- t relation will deviate only slightly from that given in NIST monograph 175.

It must be understood that performance will degrade with use. There are a number of factors which cause decalibration, such as the atmosphere to which they are held at temperature and the highest temperature used. These effects are discussed in detail in the Bibliography.

Reference Junction Corrections. The values cited are appropriate for the situation in which the reference junction is maintained at the ice point ($t_0 = 0^\circ\text{C}$). If the reference junction is not

TABLE 3-2 Standardized Thermocouples

Type designation	Nominal composition	Range, °C	Highest t for short-term service, °C
Type B	Pt – 30% Rh vs. Pt – 6% Rh	0 to 1820	1700
Type E	Ni – 10% Cr vs. Cu – Ni*	–270 to 1000	370 to 870†
Type J	Fe vs. Cu – Ni*	–210 to 1200	320 to 760†
Type K	Ni – 10% Cr vs. Ni – Al	–270 to 1370	760 to 1260†
Type N	Ni – 14% Cr – 1.5% Si vs. Ni – 4.5% Si – 0.1% Mg	–270 to 1300	760 to 1260†
Type R	Pt – 13% Rh vs. Pt	–50 to 1768	1480
Type S	Pt – 10% Rh vs. Pt	–50 to 1768	1480
Type T	Cu vs. Cu – Ni*	–270 to 400	150 to 370†

*These alloys contain roughly 55% Cu and 45% Ni, and they are known as constantan.

†The highest temperature depends on the diameter of the wire. See ASTM Standard E230, Table 2, for further explanation.

maintained at that temperature, an emf correction must be applied to the measured emf to account for this. Refer to ANSI-MC96.1 for a discussion of this correction.

Extension (or Compensating) Wires. In many situations, it may be necessary for the reference junctions to be very distant (as much as several hundred feet) from the junction measuring T . Since most of the total emf in the thermocouple is generated by the short section at elevated temperatures, very little measurement error will occur if the remaining length at room temperature is replaced by thermocouple “extension” wires. Extension wires are made from materials having nearly the same thermal emf properties as the original thermocouple but which can be made at considerably less cost. For types E, J, K, N, and T thermocouples, the extension wires are made from the same alloy as the thermocouple wire but with less stringent requirements for the composition. For types R and S thermocouples, copper wire is used for one arm of the thermocouple, while a Cu–Ni alloy wire is used for the other.

Thermocouples: Summary. Thermocouples are relatively inexpensive, small, have rapid thermal response, and produce a signal (i.e., the emf) which is easily measured by a digital voltmeter. Spools of the thermocouple wire may be purchased, and many thermocouples may be made from them. Furthermore, each thermocouple will have an emf versus temperature given to within specified tolerance of the standard table so that in many instances calibration is not necessary. There are disadvantages to thermocouples, however; the emf is sensitive to the temperature distribution along the wire, strains, thermal history, and degradation at elevated temperatures. If these latter problems outweigh the advantages, other thermometers described below may be more appropriate.

Liquid-in-Glass Thermometry. A liquid-in-glass (LIG) thermometer consists of a reservoir of liquid and a stem with a temperature scale marked on it. The liquid has a very large thermal expansion compared with the reservoir and stem, and thus small temperature changes cause the liquid to expand into the stem where the length indicates T . A wide variety of liquids and glasses are used, but the most common liquid is mercury enclosed in borosilicate glass. If properly treated, LIG thermometers are capable of repeatedly measuring T to within 0.03°C . The major cause of catastrophic failure is breakage; of noncatastrophic failure, heating the thermometer beyond its specified range. LIG thermometers are used widely throughout industry because they are inexpensive and easy to read with the human eye. They are not amenable to automation or continuous monitoring, however. In many applications, they are being replaced by thermocouples or resistance thermometers, commonly called *resistance temperature detectors* (RTDs).

Resistance Temperature Detectors. Since resistance is a physical property that is easy to measure and automate with modern instrumentation, RTDs are finding more general acceptance in temperature measurement. The two major classes of resistors with strong temperature dependence are thermistors and platinum resistors.

Thermistors. Thermistors are made by sintering mixtures of oxides of Mn, Fe, Co, Cu, Mg, or Ti, bonding two electrical leads to the sintered material, and enclosing the unit in a protective coating. The devices are made in a wide variety of shapes (beads, disks, rods, and flakes), are very inexpensive, and are very compact (one bead type commercially available is only 0.07 mm in diameter). The resistance of the device is generally high (1 to 100 k Ω), so lead resistance is not a significant source of measurement error. If glass-encapsulated bead-type thermistors are used below 150°C , they are quite stable. (Commercial units are available which drift by no more than 0.01°C per year.)

Thermistors are semiconducting devices whose resistance depends exponentially on temperature. This means that the thermistor is very sensitive to temperature, but it also means that its temperature range is limited (i.e., if T becomes too low, the resistance becomes too high to measure; if T is too high, the resistance becomes too low to measure). Thermistors may be chosen for use with temperatures as low as 4 K, while others may be used in the region near 900 K. A technique, referred to as *linearization*, may be used to extend the operating range of a thermistor. This consists of connecting a temperature-independent resistor R in parallel with the thermistor. If the value of the resistor is equal to that of the thermistor in the center of its operating range, the resistance of the circuit will be roughly linear in temperature rather than exponential.

Thermistor-based measurement systems with digital readouts which read directly in temperature are widely available. These consist of a sensor, a digital ohmmeter, and a logic unit, generally a microprocessor. The microprocessor is used to perform resistance-to-temperature conversion and perhaps integration, control timing, run a display, and provide digital output for computer analysis.

Platinum Resistance Thermometers (PRTs). The resistance of platinum is roughly linear in temperature over a very wide temperature range, and thus PRTs may be used over a greater temperature range than thermistors. Precision-type PRTs can be very reproducible and are capable of high accuracy. They are, however, more sensitive to mechanical shock and less sensitive to temperature change than are thermistors.

For the highest-accuracy temperature measurements, three types of “standard” PRTs are used. From 83.8 to 693 or 934 K, a well-characterized, fine Pt wire is supported by insulators and enclosed in a fused silica glass casing. The assembled unit is 600 mm long and 7 mm in diameter. From 13 to 84 or 273 K, a “capsule” version 60 mm long, 6 mm in diameter, with similar internal construction, is used. A third type, called a *high-temperature standard PRT* (HTSPRT), is constructed of larger wire and typically has a resistance of about 0.25 or 2.5 Ω at 273 K. That wire is wound on fused silica formers, and the overall length of the unit is about 24 in. When properly used (see NIST Technical Note 1265), PRTs may be used to measure temperature with an imprecision not exceeding ± 0.001 K over the range 13 to 934 K. Such standard PRTs are used to realize the ITS-90 over the range 13 to 1235 K. Since great care must be exercised in measuring and handling these devices in order to achieve this performance, standard PRTs are generally restricted to the primary standards laboratory of any organization.

Thermal Radiation. Radiant flux, in the form of photons or electromagnetic waves, emitted by a surface solely as a consequence of its temperature is known as *thermal radiation*. Its wavelength range extends from about 100 nm (far ultraviolet) through the visible to about 1 mm (far infrared).

Blackbody Radiation. A surface which absorbs all incident radiation, regardless of wavelength or direction, is known as a *blackbody*. For a given temperature and wavelength, such a surface will emit the maximum possible thermal radiation. The thermal power emitted by an element of area into an element of solid angle surrounding the given direction of propagation (the *radiance*) is independent of direction for a blackbody. The spectral radiance distribution of a blackbody, $L_b(\lambda, T)$, is described by the Planck equation:

$$L_b(\lambda, T) = \frac{c_1}{\lambda^5(e^{c_2/\lambda T} - 1)}$$

where λ is the wavelength of the emitted flux, T is the thermodynamic temperature of the blackbody, c_1 is the first radiation constant ($3.741832 \times 10^{-16} \text{ W} \cdot \text{m}^2$), and c_2 is the second radiation constant ($1.438786 \times 10^{-2} \text{ m} \cdot \text{K}$). A blackbody does not exist, but it can be closely approximated by a very small opening in a uniformly heated hollow opaque enclosure.

Stefan-Boltzmann Law. The relation between the total power per unit area emitted by a blackbody M_b and its thermodynamic temperature T is expressed by the equation

$$M_b = \sigma T^4$$

where σ is the Stefan-Boltzmann constant ($5.67032 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$). This equation is obtained by integration of the Planck equation over the wavelength range zero to infinity.

A real surface can never emit more thermal power than a blackbody. It is often convenient to express the total thermal power emitted by a real surface per unit area, M_s , to that emitted by a blackbody at the same temperature by the equation

$$M_s = \epsilon M_b = \epsilon \sigma T^4$$

where ϵ is the total hemispherical emissivity (note that $\epsilon < 1$).

Radiation Thermometer (Pyrometer), Wide-Band. In a wide-band radiation thermometer, thermal radiation from the source is focused on the sensor by means of a lens or concave mirror. The sensor might typically be a thermopile, a pyroelectric, or a solid-state photodiode detector. The fraction of the total thermal radiation received from the source is limited by the spectral transmission/reflection characteristics of the components in the optical path as well as the spectral response of the sensor itself. For measurement of the temperature of a blackbody source, the relation between the output of the sensor S and the temperature of source T_s can be approximated by the equation

$$S = a\sigma T_s^b$$

where a and b are instrumental constants obtained through calibration. With suitable linearization circuitry, the output of the instrument can indicate temperature.

Radiation Thermometer (Pyrometer), Spectral-Band. In a spectral-band radiation thermometer, thermal radiation from the source is typically focused on the sensor by means of a lens. The bandwidth of the thermal radiation reaching the sensor is defined by a transmission filter placed in the optical path within the instrument. The sensor found in most instruments is a solid-state photodiode detector. For measurement of the temperature of a blackbody source, the output of the detector is approximately proportional to the Planck equation.

With suitable linearization circuitry, the output of the instrument can indicate temperature. Many narrow-band instruments have a control which can be adjusted by the operator to compensate for the emissivity of the source.

3.4 ELECTRICAL MEASUREMENT OF NONELECTRICAL QUANTITIES

A *transducer* is a device in which variations in energy of one form produce corresponding variations in energy of another form. In common usage, either the input or output of a transducer is electrical. Thermocouples and thermistors fall into that category, as does the *thermal converter*, whose electrical output (dc millivolts) is derived from a thermal effect that represents an electrical quantity (ac volts, current, watts, vars) that differs in nature from the output. A variety of methods is often available for the measurement of a specific variable. "Frequently, operational considerations will indicate the choice of transducer; for instance, piezoelectric transducers may not perform well if long cables are required; capacitive devices, although quite sensitive, may require intermediate electronic circuitry; and magnetic transducers should not be used in the presence of strong magnetic fields."

Mechanical displacement may be converted into an electrical variable by the simple expedient of adjusting resistance in an electric circuit. A slide-wire resistor, having a movable contact attached to the part whose displacement is to be measured, may be connected through a 2-conductor circuit to a steady-voltage source in series with an ammeter (or milliammeter) calibrated in terms of the displacement. If the resistor is connected as a voltage divider, the need for a regulated supply is eliminated, and with a 3-conductor circuit the display instrument may be a ratio meter or a potentiometer. Such combinations are common and are available for both dc and ac operation. Where deflections are small—less than 0.1 in—measurement may be made by use of a differential transformer.

In the *strain gage*, microscopic relative displacements are electrically magnified and are displayed on an indicating or a recording meter or on an oscillograph. Modern resistance-type strain gages comprise fine-wire windings arranged to be more or less elongated when subjected to deformation. The units may be used singly, in pairs, or in sets of four constituting a complete Wheatstone bridge. There are two main classes of wire-wound strain gages, (1) bonded and (2) unbonded.

1. The *bonded strain gage* is composed of fine wire, wound and cemented on a resilient insulating support, usually a wafer unit. Such units may be mounted on or incorporated in mechanical elements or structures whose deformations under stress are to be determined. While there are no

limits to the basic values which may be selected for strain-gage resistances, a typical example may be taken as of the order of 100 to 500 Ω .

2. In the *unbonded strain gage*, the resistance structure comprises a fine-wire winding stretched between insulating supports mounted alternately on the two members between which displacement is to be measured (Fig. 3-42). These wires comprise the four arms of a Wheatstone-bridge network of which two opposite arms are tightened and the other two are slackened by the displacement. While a bonded gage tends to respond to the average strain in the surface to which it is cemented, the unbonded form measures displacement between the two points to which the respective supports are attached. Unbonded wire strain gages are usually operated on input potentials ranging up to 35 V direct or alternating current. Under conditions of extreme unbalance, corresponding to full operating range, the open-circuit emf may be of the order of 8 to 10 mV and the closed-circuit current up to 100 μ A.

Recently developed types of conductive rubber are used in resistive transducers capable of wider ranges of deformation than are those using wire or foil. Where the strain gage must operate over a temperature range, dummy gages exposed to the temperature but not the strain may be employed for temperature compensation, or alloys having a low temperature coefficient of resistance may be used. Piezoelectric strain gages are also available for applications in pressure, force, torque, and displacement measurement. Strain gages for use on ac circuits are supplied in both capacitive and inductive forms, wherein the corresponding characteristics of ac circuit components are varied by the displacements to be measured.

A popular means for measuring *small displacements* in the range from a millimeter to a micron is the *linear, or differential, transformer*. This device is generally produced with a single primary winding and two secondaries, all disposed along a common axis and having in the common magnetic circuit a movable iron core longitudinally displaceable with the motion to be measured. The secondaries may be connected additively or differentially and may be included in the circuit of a null-type instrument balanced either by shifting the core of a similar transformer excited from the same source or by the use of a slide-wire potentiometer. Linear transformers are regularly supplied for operation at all frequencies up to 30,000 Hz. The sensitivity, of course, increases with the frequency. Linear transformers may be interconnected in a great variety of arrangements to perform computations or to express desired mathematical functions of measured variables.

Strain gages permanently attached to diaphragms, tubes, and other pressure-sensitive elements find wide applications as components of *electrically actuated pressure gages*. By electrically combining simultaneous measurements of torque and velocity, continuous determination of mechanical power may be obtained, the combination becoming an electrical-transmission dynamometer.

Vibration may be determined by a strain gage, but the fact that this magnitude involves motion renders it generally preferable to utilize alternating potentials developed by periodic change in the geometry of the measuring circuit. This may be embodied in either a *capacitor* or an *inductive device*. In a recently developed apparatus, there are no moving parts except the object being shaken,

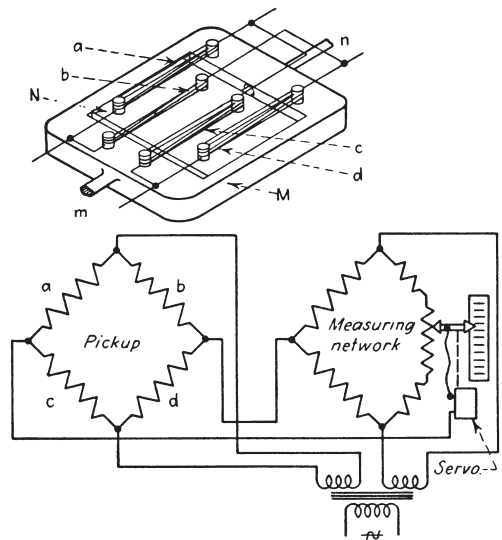


FIGURE 3-42 Diagram of unbonded wire strain gage. Supports *M* and *N* are attached by rods *m* and *n*, respectively, to points between which displacement is to be measured. Pickup and measurement networks are energized from similar but isolated sources. Unbalance originating in the pickup is detected and balanced by a servo-actuated measuring network, providing a reading of strain on a graduated scale.

and the vibration displacement is sensed by its effect on an electrostatic field between the pickup and the moving part. *Piezoelectric crystals* are particularly adapted to the measurement of vibration. The emf so obtained is proportional to the amplitude of deflection multiplied by the frequency squared.

Air velocities and the *flow of gases* in general may be measured by the *hot-wire anemometer*. In its simplest form, this device utilizes the cooling effect of the gas stream to establish a temperature difference between exposed and protected bridge arms. Where the flow is in an enclosed conduit, a heating element may be introduced and the volume of flow determined by the amount of heat transferred between the heater and the temperature-sensitive bridge wires.

Flow of an electrically conducting liquid may be determined by measuring the emf developed between a pair of electrodes set in opposite sides of an insulating conduit due to the movement of the liquid through a magnetic field established transversely of the conduit and perpendicular to both the flow and the line joining the electrodes (Fig. 3-43). By using an alternating field, the effects of electrode polarization may be eliminated. Null measurement of the generated voltage renders the apparatus independent of the resistance of the liquid.

Liquid level may be expressed electrically by the use of a transducer responsive to the vertical position of a float or by a pressure-sensitive strain gage immersed in the liquid below its lowest level. Variation in resistance of an immersed conductor is a widely accepted principle, especially in fuel tanks. If the liquid is an electrical insulator and of constant characteristics, its depth may be determined by its dielectric effect between a pair of vertically disposed capacitor plates. On the other hand, if the liquid is a conductor and very small changes in level are to be detected or regulated, the liquid may be made one electrode of a capacitor whose other electrode is a horizontal plate positioned above the surface.

Levels of corrosive liquids or those operating under extreme pressures, temperatures, or other conditions rendering them inaccessible for measurement by conventional means may be determined by the use of *gamma radiation*. Several gamma-ray sources are spaced at equal vertical intervals in the tank or reactor containing the liquid to be measured but are positioned so that none of them obstructs the line of sight of a Geiger counter tube placed at the top of the container. The response of the Geiger tube depends on the depth of the process material, and the output is measured on a null-type recording instrument.

Vacuum may be measured by determining either *energy dissipation* or electron emission in the space under test. The former principle provides the basis of the *Pirani gage*, wherein two similar heated filaments forming arms of a bridge are located, respectively, in a reference bulb and a bulb connected to the evacuated space. Heat dissipation will vary with the degree of evacuation, while conditions in the reference bulb remain constant. The electrical condition of the bridge then provides a continuous measure of the vacuum. The normal range of operation of the Pirani gage is from 10^{-7} to 5 torr. Since the performance of a thermionic tube is highly responsive to the degree of vacuum, its action under controlled electrical conditions is a criterion of internal atmosphere. This principle forms the basis of a number of *electronic vacuum gages*. The normal range of operation lies between 10^{-7} and 10^{-3} torr.

Electrical methods for *analyzing gases*, while essentially thermal in their nature, are made practicable only by the application of electrical principles in determining thermal relationships. In the *thermal-conductivity method*, as best exemplified in the CO_2 recorder, two cells or sections of conduit containing, respectively, a standard sample and the gas under test have in them adjacent arms of a bridge network composed of wires having known resistance variation with temperature and carrying sufficient current to raise their temperatures appreciably above their surroundings. As more or less heat is dissipated in the test cell as compared with the reference cell, the relative resistance of the bridge arms varies, providing an electrical basis for measurement of the gas composition.

The *catalytic-combustion method* is especially adapted to *detection of flammable gases* or determination of explosibility. The arrangement of cells and bridge wires may be similar to that of the thermal-conductivity type, but the filament is usually composed of activated platinum and is operated at a temperature sufficient to ignite the gas when a critical proportion is attained. The increased

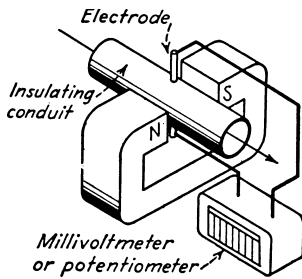


FIGURE 3-43 Electromagnetic flowmeter.

heating of the bridge wire due to combustion abruptly disturbs the balance and provides a positive indication of explosibility. In some forms of this instrument, the temperature rise is determined by thermocouples. The catalytic-combustion method is useful in determining mixtures containing such gases as propane, acetone vapor, carbon disulfide, and carbon monoxide. The equipment finds use in (1) solvent-recovery processes, (2) solvent-evaporating ovens, (3) combustible-gas storage rooms, (4) storage vaults, (5) gas-generating plants, (6) refineries, and (7) mines.

In determining the *oxygen content of gases*, both the conventional thermal-conductivity method and the catalytic combustion method are applicable. In addition to these, use is made of the *magnetic susceptibility* of oxygen as a basis of operation. In one such instrument, a hot-wire bridge similar to that of a CO₂ recorder is employed, one of the gas chambers being placed in a strong magnetic field. This stimulates the flow of oxygen-containing gas through that chamber, thereby unbalancing the bridge by a measurable amount. In the other magnetic analyzer, a test chamber contains a small magnetic member rotatable in a distorted field whose conformation depends upon the amount of oxygen present. The resultant angular displacement of the test member may be used similarly to that of a galvanometer in either a direct-deflecting or a null-type instrument.

An analyzer especially suited to measurement of *toxic ionizable gases* or vapors to and beyond the toxic limits utilizes the electrical conductivity of an aqueous solution of the gas. The vapor under test is bubbled through distilled water at a fixed rate, and the conductivity of the solution becomes a measure of gas concentration. A typical use is the continuous recording of small quantities of substances like sulfur dioxide, hydrogen sulfide, chlorine, and carbon disulfide in the air.

Atmospheric contamination may be determined by an *electronic leak detector*, utilizing emission of positive ions from an incandescent filament exposed to the air. The filament is enclosed in an open inner cylinder and heated by alternating current. The atmosphere under test is forced through the annular space between the inner and an outer cylinder at a predetermined rate, and the electron flow due to a dc potential maintained between the cylinders is measured as an index of the amount of contaminant. Presence of extremely small proportions of halogen vapor compounds, of which Freon, chloroform, and carbon tetrachloride are good examples, greatly increases the emission. At room temperatures, the device does not respond to Pyranol, but if this material is heated sufficiently to give off vapor, a response is obtained. It also responds to solid particles of the halogens and therefore will detect *smoke* from burning materials containing these elements. The instrument is also available as a recorder and/or a controller.

Relative humidity is determinable electrically by methods involving either of the two basic principles: (1) variation of electrical conductivity or of dielectric constant of a hydrophilic element and (2) computation based on "dry-bulb" and "wet-bulb" temperatures of the atmosphere whose moisture content is to be determined. The most common embodiment of the former method consists of an insulating card, plate, or cylinder carrying a bifilar winding of conductive wire and having a relatively large surface exposed to the atmosphere. The two strands of wire are bridged by a coating of material such as lithium chloride or colloidal graphite, having a high affinity for moisture. This material quickly assumes a water content corresponding to that of the atmosphere, and the electrical resistance between the conductors becomes a function of the humidity to be measured. A similar principle is used in determining the moisture content of hygroscopic materials such as wood, grain, or pulp. In such applications, a resistance-measuring circuit terminates in electrodes or probes which are pressed against or inserted into the material to be tested.

Moisture content of material in a web or sheet form, such as paper, may be continuously determined by passing the web between the plates of a capacitor, and thus obtaining a measurement determined by the dielectric constant of the material as affected by its water content.

Electrical determination of humidity by the wet-and-dry-bulb method requires somewhat intricate computing circuits which for accurate results must take account of absolute temperature and barometric pressure.

Determination of dew point, or the temperature at which condensation takes place on a polished surface, as a function of absolute humidity, employs essentially a thermal and optical method of measuring, but such a system may be rendered continuous and automatic by photoelectrically observing the conditions of a polished surface in the tested atmosphere utilizing a servo system to regulate its temperature and thus obtaining an indication or a record of the dew point.

The two most popular types of *electric micrometers* are (1) that utilizing the magnified output of a strain gage and (2) that based on precise determination of capacitance between two electrodes whose spacing corresponds to the measured dimension.

Ultrasonic thickness gages may be used to measure steel walls ranging in thickness from $\frac{1}{8}$ in to 1 ft, utilizing the fact that sound vibrations tend to establish standing waves within the mass of the material upon which they are impressed. This device combines a variable-frequency oscillator with a piezoelectric crystal which is pressed against the wall to be tested. The circuit is tuned until the metal oscillates, causing a sharp increase in the loading. The frequency of this resonance indicates the thickness of the material.

Selection of a method for determining the *thickness of sheet material* in process will depend primarily on the inherent electrical conductivity of that material. If it is essentially a nonconductor, such as rubber, plastic, or paper, measurement may be continuously performed by passing the sheet or web between the plates of a capacitor. (In such measurements on hygroscopic materials, moisture content may become a dominating factor.)

Sheet thickness in sheet materials, whether conducting or insulating, may be measured by the *beta-ray gage*. In this device, a stream of beta rays passes through the sheet to a pickup head whose response is amplified and continuously recorded and, if desired, made the controlling influence in automatic regulation. Provision is made for the combined radiation source and pickup to traverse the strip of material and scan its whole width.

Thickness of coatings, such as varnish or lacquer, on conducting materials may be determined by a continuous measurement of capacitance between the base and a reference electrode, the coating being included as a dielectric. With a magnetic base, such measurement may be performed effectively by determining the effect of the coating on the gap in a magnetic circuit.

Surface roughness may be determined either on an absolute basis or by comparison with a "standard" surface. A common method involves passing a small stylus systematically over the surface, similarly to a phonograph needle, and measuring the resulting vibration. The stylus may be attached to a strain gage, piezoelectric crystal, or a magnetic pickup. The resulting alternating emf may be amplified and displayed on an oscillograph, or it may be rectified and measured with a millivoltmeter. A basis for quantitative determination of surface roughness is found in USAS B46.2.

An absolute method of determining roughness uses the electrical capacitance of the tested surface in contact with an electrolyte as compared with that of an ideal (mercury) surface. On the assumption that the capacitance varies as the surface area, the comparison provides a figure representing the ratio of the tested surface to one of perfect smoothness.

Transparency (or opacity) determination of materials and continuous monitoring of smoke density involve passing the substance to be examined through the path of a light beam directed upon a photocell. Uninterrupted measurement is made by means of a potentiometer or a bridge, according to the class of cell employed.

Viscosity measurement is essentially mechanical in its nature, and the application of electrical methods consists of determination of stress or displacement set up in the measuring apparatus owing to the characteristic of the fluid. One method involves measuring the electrical input to a small motor driving an impeller or stirrer in the fluid. Another method is based on electrical determination of the angle of lag (torque measurement) in a resilient mechanism through which an impeller is driven. A further method utilizes *magnetostriction* to produce longitudinal oscillations in a steel rod carrying a diaphragm immersed in the liquid. Determination of the electrical loading on the exciting circuit provides a measure of viscosity.

Electrical measurement has superseded many of the older methods of quantitative determination of *chemical magnitudes*. The two best-known methods are based, respectively, on the electrical *conductivity* of solutions and on the *voltaic effect* in specific cells. The basic principles of these measurements are wholly different, as are their applications. In the *conductivity* cell, every precaution must be observed to avoid electrolytic effects, the prime requisite being that the respective electrodes be of identical material. Even then, the passage of current or the application of the potential tends to produce internal polarization emf in the cell. This undesirable effect may be almost wholly eliminated by measuring electrolytic resistance with alternating current, and the highly sensitive ac detectors now available enable such tests to be made with precision. Outstanding among the uses of the

resistance cell is determination of the *purity of water* for domestic and industrial purposes. Conductivity of water solutions usually increases in proportion to the amount of dissolved electrolytic material. Perfectly pure water has a specific resistivity of 18 to 20 million Ω/cm^3 , but in practice, such values are virtually unobtainable. Only by careful distillation or deionization is it possible to obtain water of 400,000 to 800,000 specific Ω at a reference temperature of 20°C. Continuously operating water-conductivity recorders are supplied for use with commercial ac power supply, and a typical range is 100,000 specific Ω to infinity.

Electrolytic cells utilize measurement of emf developed between a standard combination of electrodes by the solution under test. Development of the principle has reached its highest refinement in the measurement of pH, or hydrogen-ion concentration, which is a criterion of the activity with which the solution will enter as an acid into a chemical reaction. The pH value is a logarithmic function of the emf developed with a given strength of the solution in a specified cell. For pure water, which is “neutral” in its reaction, lying midway between the acids and the bases, the pH value is 7. The pH measurement is essential in practically every industry involving any chemical process, as well as in waterworks, sewage systems, biological laboratories, and agricultural experiment stations.

3.5 TELEMETERING

Telemetering is measurement with the aid of intermediate means which permit the measurement to be interpreted at a distance from the primary detector. The distinctive feature of telemetering is the nature of the translating means, which includes provision for converting the measurand into a representative quantity of another kind that can be transmitted conveniently for measurement at a distance. The actual distance is irrelevant.

Electric telemetering is telemetering performed by deriving from the measurand or from an end device a quantitatively related separate electrical quantity or quantities as a translating means. A *measurand* is a physical quantity, property, or condition which is to be measured.

Telemetering has been practiced many years in the central-station industry and in the transmission and distribution of electric power but until lately only to a limited extent in the nonelectrical fields. With the phenomenal expansion of pipelines for gas and for oil, the need has vastly increased, and electric telemetering installations have become indispensable in the remote measurement, totalization, regulations, and dispatching of these utilities. Telemetering also has found wide application in extensive industrial plants, such as refineries, steel mills, and large chemical plants, and in these installations it often forms an essential part of remote regulating apparatus.

There has been a rapidly increasing use of telemetering in aircraft, meteorology, ordnance, and guided missiles. This has led to a sharp demarcation of telemetering philosophies and techniques into two classes, *mobile* and *stationary*. In the former, the apparatus is expected to operate for a very short period of time—often only a matter of seconds. The transmitting unit at least must be considered as expendable, and the combination is generally subject to an overall calibration for each isolated test in which it is used. Obviously, there can be no interconnecting physical circuit, and a radio link is an essential part of the system.

Stationary systems in general involve transmitting and receiving units at fixed locations. These are usually of a permanent nature and are intended for operation over extended periods of time. Signal transmission between the stations usually involves a physical circuit, and even where radio principles are utilized, the most common practices require guiding of the signal by means of a more or less continuous conducting path.

A *telemetering system* incorporates the same three essential elements as are required in a system for measurement of nonelectrical quantities by electrical means, namely, a *transmitting unit* (transducer or pickup), a *receiving unit* (an instrument for measuring an electrical variable), and an *interconnecting circuit* or channel by which the electrical variable (signal) originating at the transmitter is carried to and impressed upon the receiver.

In transmission of measurement over considerable distances, the *circuit* or *channel* may become the predominating factor in the system. In the ideal telemetering system, the terminal apparatus

would be inherently self-compensating so that variations in circuit conditions would not adversely modify the signal. Merit of a telemetering system is directly related to the degree to which it approaches this ideal. Distance criterion of a telemetering system is not so much the number of feet or miles over which it will operate as it is the nature and magnitude of circuit impedance through which its signals will maintain their identity and proportionality. Since the data have been determined for specific types of circuits and channels, such magnitudes generally may be expressed in units of distance. A continually increasing proportion of telemetering is being carried out over circuits and channels leased from communication companies. With information available respecting the type of signal to be transmitted, the telephone or telegraph company provides a suitable circuit and assumes responsibility for its operation. Where privately owned circuits are used for telemetering, their maintenance and protection correspond to those for comparable communication circuits.

In *classifying telemetering systems*, the ANSI has adopted a grouping recommended by the AIEE and based on the nature of the electrical variable transmitted through the interconnecting circuit or channel. The names of the five classes are more or less self-explanatory and are as follows: *current*, *voltage*, *frequency*, *position*, and *impulse* types. In each of the first three of these classes, the corresponding characteristic of the electrical output of the transducer comprising the transmitting unit is varied with variations in the measurand. In the *position* system, the quantitative ratio, or the phase relationship, between two electric voltages or currents determines the nature of the transmitted signal, usually requiring a circuit of three or more conductors. There are several *impulse* systems, in all of which the transmitting instrument acts to “key” a signal impressed on the circuit, producing a series of successive pulses which, according to their nature, are interpreted by the receiving instrument and expressed in terms of the measurand.

Telemetering systems are not always mutually exclusive. A single installation may represent a combination of several of the named systems. In some instances, it becomes difficult to decide into which of the specified classes a particular method of telemetering may fall.

Telemetering of electrical quantities, such as volts, watts, and vars (volt-amperes reactive power) presents a problem owing to the inherently low torque of direct-deflecting instruments, whereas devices for measuring such quantities as position, flow, and liquid level are not subject to such restrictions. Accordingly, where measurements of electric units are to be transmitted, practice favors those systems which place a minimum of burden on the primary measuring instruments and preferably those adapted to transmitters having no moving parts. Thus, photoelectric, thermoelectric, and capacitive transmitters have found considerable favor in the electric industry.

In transmitting measurements originating in *integrating meters*, such as watt-hour or var-hour meters, the mechanism of the meter, either by photoelectric or electronic means or by a contact arrangement, is caused to develop a series of electrical pulses whose frequency of occurrence is proportional to the instantaneous value of the measured load. By a simple electronic network including capacitors charged and discharged at the frequency of the pulses, there is produced a direct current whose value is proportional to that frequency, the telemetering system being thus placed in the *current* class. On the other hand, the pulses may be directly impressed on the communication channel, whereupon the system falls into the *frequency* group.

Where the basic measurement is performed by a low-torque instrument of the direct-deflecting class, such as a wattmeter, common telemetering practice involves either *balancing the torque* or matching the deflection of the instrument by the effect of an automatically regulated direct current in the winding of a permanent-magnet moving-coil mechanism. This current, remaining proportional to the instrument torque, is transmitted through a metallic circuit for measurement at the receiving station and, if desired, may be included with other and similar currents in a load totalization.

A most flexible method for the transmission and totalization of electric power measurements involves the use of a *thermal converter*. The several commercial forms of this device operate on a long-known but only recently applied principle combining the circuit of the thermal wattmeter with that of the thermocouple. In the former, the temperatures of two resistors are caused to assume values differing by an amount proportional to the power in the measured circuit. In the latter, there is developed an emf proportional to the temperature difference or to the *power* in the measured circuit, irrespective of power factor, frequency, or waveform. Thermal converters are supplied in single-element, two-element, and three-element forms, and the ac input circuits may be wired into the instrument-transformer secondaries on any conventional polyphase power system. The output from the dc terminals is either measured

directly or interconnected with that of other converters to provide totals of measured loads. The full-load potentials are usually rated at 50 or 100 mV, according to make and type, and measurement is preferably made with a self-balancing potentiometer. For best results, thermal-converter output circuits, which, of course, must be wholly metallic, should be well shielded from parasitic electrical effects and preferably should be in a sheathed cable. An advantage of thermal-converter installations, even for relatively short distances within the plant, is that the seven or eight conductors necessary for connecting instrument-transformer secondaries to wattmeters or varmeters are replaced by two small wires operating at a negligible power level. Furthermore, physical damage to the output wiring, whether in the nature of an open circuit or a short circuit, is not hazardous to equipment or personnel, and on restoration of the circuit, normal operation will be resumed without loss of accuracy.

Electrical impulses may be used as signals for telemetering in a number of ways, the most important in stationary installations being that based on *frequency* and that based on *duration* of successive impulses. Impulse systems are to telemetering what telegraphy is to other forms of communication. The function of the transmitting instrument is essentially one of “keying” a circuit. Since the significance of the transmitted signal is based on time only, it follows that the method is most nearly immune to circuit conditions, such as voltage variation, impedance changes, attenuation, poor connections, and pickup from adjacent disturbing influences. Impulses whose frequency represents the measured variable may be transmitted as such, then falling into the category of the *frequency system of telemetering*, or they may be converted into a proportional direct current and be classified with the *current systems*.

Impulse-Duration Telemetering. Signals recur at uniform intervals, and each has a duration corresponding to the then existing value of the measured magnitude. The transmitting instrument includes a constantly running cam or scroll plate having a spiral trailing edge and operating in the plane of the pointer but perpendicular to the line of excursion. At a fixed point in each revolution of the cam, the pointer is engaged and brought against the cam face until subsequently released by the trailing edge. With engagement and disengagement, the pointer is slightly deflected perpendicular to its line of travel and actuates a contact in a signal circuit. Because of the spiral form of the trailing edge, the length of the signal depends on the position of the pointer and thus represents the measured variable.

The receiving unit includes the equivalent of a pair of electromagnetic clutches continuously driven by a constant-speed motor. These clutches are actuated by the incoming signals, one in an “upscale” and the other in a “downscale” sense, according to whether the transmitter pointer is on or off the cam. The receiver pointer or pen is frictionally retained in position and is “nudged” alternately toward one end or the other of its range by impellers or “dogs” carried by the clutches and, respectively, reset to zero as the corresponding clutch is released. Thus, with each signal, the receiver pointer finds or maintains a position corresponding to that of the transmitter pointer.

Position Telemetering. In the *position system* of telemetering, the characteristic signal involves the relationship between two electrical quantities of a similar nature, that is, two voltages or two currents. Unless carrier is used, position systems (with one exception) require an interconnecting circuit of three or more conductors. The simplest position-telemetering arrangements are those of the rheostatic, or bridge, type, either direct or alternating current. Mechanical attachment of the measuring element to a voltage-dividing resistor provides a transmitting unit wherein the relative value of two voltages may be made proportional to the measured quantity. The receiving instrument may take the form of a ratio meter or may be a self-balancing bridge. The accuracy of such systems is affected by the impedance of the interconnecting circuit, but by maintaining this value small in comparison with that of the terminal instruments, the error may be made negligible for considerable lengths of line.

Selsyn. The inductive type of position system is best exemplified in the “selsyn” position motor or any one of its several equivalents. The transmitting and receiving units may be identical in structure. Each involves a stator and a rotor, one being provided with a single-phase and the other with a polyphase winding. The single-phase windings are excited from a common ac source, and the polyphase windings are interconnected. The rotors of the two units will tend to assume duplicate angular positions so that if one is attached to a measuring element, the other will provide a remote

indication of its position. This system requires three line conductors in addition to the pair comprising the common power supply. The versatility and flexibility of the *differential transformer* render it particularly adaptable to telemetering of mechanical displacements.

Totalization of power loads and of other measured quantities may readily be effected in the current or voltage systems by connecting the outputs of the respective transmitters in parallel or in series, as the case may be. Subtotals and other mathematical functions also may be obtained. Telemetering, especially totalization and retransmission, is greatly facilitated by the power and flexibility of servo-actuated potentiometers and bridges. With these instruments available, there is practically no limit to the possibilities of telemetering, not only in the electrical-utility field but, also in association with pipelines and large industrial plants. By *multiplexing* the circuits, it is possible for several telemetering transmitters and receivers to share a common communication channel. The most common systems of multiplexing are those based on *frequency* and those based on *time*. The frequency method transmits the signals on carriers having a specific frequency allotted to each transmitter and receiver combination. Time multiplexing involves the use of a multiple-point switch at each end of the circuit. These switches are progressively advanced at definite intervals, providing connection successively between each receiver and its corresponding transmitter. After a predetermined number of operations, a distinct synchronizing signal checks and, if necessary, adjusts the relative position of the switches at the transmitting and the receiving stations.

3.6 MEASUREMENT ERRORS

The complete statement of any measurement result has three elements: the *unit* in terms of which the result is stated; a *numeric* which states the magnitude of the result in terms of the chosen unit; and its *uncertainty*, the experimenter's estimate of the range within which the result may differ from the actual value of the quantity. Any physical measurement is uncertain to some extent, and errors are present in all phases of the measurement process, including the standards used to calibrate the system. Values assigned to local reference standards have uncertainties accumulated from the entire measurement chain extending back to the national reference standards that maintain a common measurement base. These national reference standards are themselves the experimental realization of the units defined in terms of the seven base units of the International System of Units (SI), and their assignments include an uncertainty estimate.

The Measurement Base. In most measurements, we are concerned only with their conformity within the technical community in which we work; our error chain stops at the national reference standards which maintain the *legal* units of the country, and our uncertainty estimates are based on these legal units. Rarely, when our concern is with the international measurement community or with basic science, must our uncertainty also include that of the maintained national unit.

Sources of Error. In addition to uncertainties in the calibration of a measurement system (which must be accepted as systematic errors in its operation), there are a number of error sources (some systematic and some random) in its operation. These operational error sources include noise, response time, design limitations, energy required by the system, signal transmission, system deterioration, and ambient influences.

Noise is any signal that does not convey measurement information. Disturbances generated within the system or coming from outside make up the background against which the desired signal must be read. Noise signals may be picked up by electrical or mechanical coupling between an external source and an element of the system, and may be amplified within the system. Under the most favorable circumstances, where noise has been minimized by filtering, by component selection, and by shielding and isolation of the system, there are still certain sources of noise present, resulting from the granular nature of matter and energy; the structure of phenomena is not infinitely fine-grained.

These fluctuations may be small compared with the total energy transfer involved in most measurements, yet they do give rise to a noise background that limits the ultimate sensitivity to which a measurement can be carried. Such sensitivity-limiting mechanisms include the brownian motion of a mechanical system, the Johnson noise in a resistance element, the Barkhausen effect in a magnetic element, and others.

The *response time* of a measuring system may contribute to measurement error. If the measured signal is not constant, lag in response results in an indication that depends on a sequence of values over a previous time interval.

Design limitations which contribute to measurement uncertainty include friction and resolution. Because a certain minimum force is needed to overcome friction and initiate motion, there results uncertainty in the rest position of an indicator. Resolution is the ability of the observer to distinguish between nearly equal quantities.

In an optical system, resolution is stated as the smallest angle at which points can be distinguished as separate. If the components of the optical train were perfect, resolution would be limited by the effective aperture of the system and the wavelength of the light used. If a scale is to be read to determine magnitudes, resolution is limited to the smallest fraction of a scale division that can be read with certainty. Most observers will attempt to estimate tenths of a division, but they generally have individual bias patterns that make a reading uncertain by 0.1 to 0.2 division.

Energy extracted from the measurand to operate the system alters the measurand to some extent, and if the available energy is small, this contributes to error in the result. Where energy is supplied from an auxiliary source, coupling or feedback may alter the measurement result. In the *transmission* of information from sensor to indicator, the signal may be distorted by selective attenuation or resonance in a communication channel, or it may suffer loss by leakage. Physical or chemical *deterioration* or other alterations of elements in the system can contribute to measurement error. Of the *ambient influences* affecting a measurement, temperature is the most pervasive. Other influences, not so universally important, include humidity, smoke and other air contaminants, barometric pressure, and the effect of gravity on an unbalanced system.

Classes of Errors. In estimating the uncertainty of a measurement result, two classes of error must be considered: systematic (which bias the result) and random (which produce scatter). *Systematic errors* are those which are repeated consistently with repetition of the measurement. Errors in the calibration of the system are systematic; uncertainty in the assigned value of a standard used in calibration must be accepted by the user as systematic. Changes of components through aging or deterioration produce systematic errors, as does failure to take into account energy extracted from a low-level source by the system. In attempting to search out and evaluate systematic errors, repetition of the measurement with definite, known changes in those parameters that are under the operator's control can be helpful, as is the use of different instrumentation or a different method. In some instances, it is possible to measure something similar to the measurand, which is independently and accurately known.

Random errors are accidental, fluctuating in an unpredictable manner. In any repetitive measurement, observations are influenced by many factors, the parameters that the observer cannot control and the residue of those he or she attempts to control. It is reasonable that combinations of these influences that add to produce large excursions are less frequent than those which partly compensate to produce small excursions, since each is equally likely to produce a positive or a negative departure. In effect, the results of a repetitive measurement process approximate a probability distribution, and it is convenient to treat the scatter of such a process as though it followed the laws of probability.

Evaluation Data. Assuming that the data from a repetitive measurement approximate a normal statistical distribution, we say that (excluding systematic errors) the mean of a group observations of a measurand is the *best approximation* of its actual value we can make from those data. Further, we estimate the imprecision of the result by certain statistical procedures. These procedures have validity only for random errors; systematic errors are not amenable to statistical treatment.

Standard Deviation. A measure of the dispersion of a set of observations is the root mean square of the deviations of individual observations from the mean of the set, $s = \sqrt{\sum d_m^2 / (n - 1)}$, where n is the number of observations and d_m is the departure of an individual from the group mean. If the number is large, the standard deviation is $\sigma = \sqrt{\sum d_m^2 / n}$. If the number of observations is small, a reasonable approximation of s can be calculated easily and quickly from the range r , the difference between the largest and smallest observation of the set $s \cong r/\sqrt{n}$ ($3 \leq n \leq 12$).

Probable Error. The probable error (pe) of an observation is that deviation from the mean for which the chances are equal that it will or will not be exceeded. If the number of observations is large, $pe = \pm 0.6745\sigma$. While this figure correctly expresses the range in which the chances are equally good that the actual value of the measurand will or will not be found (excluding systematics), it actually has no more significance as a precision index than the standard deviation from which it is derived. Thus, pe has fallen into disuse in current practice, although it was much used in the earlier literature as an index of precision. The pe of the mean of a set of observations is the amount by which the group mean can be expected to differ from the actual value of the measurand (excluding systematics) with a 50% probability. It may be calculated as $\pm 0.6745\sigma/\sqrt{n}$.

Confidence Intervals. Probable error is a special case of a broader concept. A *confidence interval* is the range of deviation from the mean within which a certain fraction of the observed values may be expected to lie, and the probability that the value of a randomly selected observation will lie within this range is called the *confidence level*.

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